ESD-TR-90-088

(2)

Technical Report
896

Millstone Angle Calibration 1989

A.L. Williams

14 September 1990

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

Prepared for the Department of the Air Force under Contract F19628-90-C-0002.

Approved for public release; distribution is unlimited.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

MILLSTONE ANGLE CALIBRATION 1989

A.L. WILLIAMS
Group 91

TECHNICAL REPORT 896

14 SEPTEMBER 1990

LEXINGTON MASSACHUSETTS

ABSTRACT

Calibration of the Millstone Hill radar is accomplished by the use of several calibration models. This report focuses on the two models used to calibrate azimuth and elevation. Data from both low-altitude and deep space satellites for the year 1989 were used for this study. Of particular interest is the variation of the calibration model parameters over time. This study considers the methods by which these parameters should optimally be determined, and the frequency with which they should be updated. In addition, attempts to model an unexplained jump seen in elevation residuals are discussed. Finally, the tiltmeter calibration models are examined. (RH)

ACKNOWLEDGMENTS

E. M. Gaposchkin provided the initial impetus for this project. I am grateful to him for his suggestions and help. J. Sciegienny provided answers to several questions and assistance with comparisons to the current method of computing the azimuth rail model parameters. T. A. Cott kindly added the ability to retrieve tiltmeter data from SATCIT raw data tapes to his program SATSNR and provided the program for my use.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

During the past year, a comprehensive study of the azimuth and elevation calibration models used at Millstone has been conducted. The methods used for calibration are based on precision orbit determination, done by the program DYNAMO, for several spherical satellites: Lageos (SSC# 8820), EGP (SSC# 16908), and Etalon (SSC# 19751). Pertinent data for these satellites is given in Table 1-1. One of the output files produced by DYNAMO, the "punch" file, contains residuals for each metric observation. These residuals are the difference between the observed and the calculated values of the metric. DYNAMO runs for each of these satellites are performed in a weekly calibration fit procedure [1].

There were three main areas of study. First, the angle calibration models used by SATCIT [2] were investigated. Particular areas of interest were the fluctuation over time of the model parameters, the methods by which the parameters should optimally be determined, and the frequency with which the parameters should be updated. The second area of study was the "elevation jump" phenomenon sometimes seen in the DYNAMO elevation residuals. A plot of elevation residuals versus time for a single satellite pass quite often shows a sudden jump in the elevation residuals; the time of this jump is usually very near the time of closest approach of the satellite. Examples are shown in Figure 1-1. This effect has been described in some detail in Reference 3. At that time, no satisfactory explanation for this effect was found; in this study another attempt to find an interpretation was made. The third area of study looked into the tiltmeters, to determine the size of the tiltmeter corrections relative to the total residual and to see if any relationship between tiltmeter calibration and the elevation jump phenomenon could be found.

TABLE 1-1.

Satellite Characteristics

Satellite	SSC No.	Diameter (m)	Weight (kg)	Altitude (km)
Lageos	8820	0.6	406	5890
EGP	16908	2.1	685	1500
Etalon	19751	1.3	1415	25503

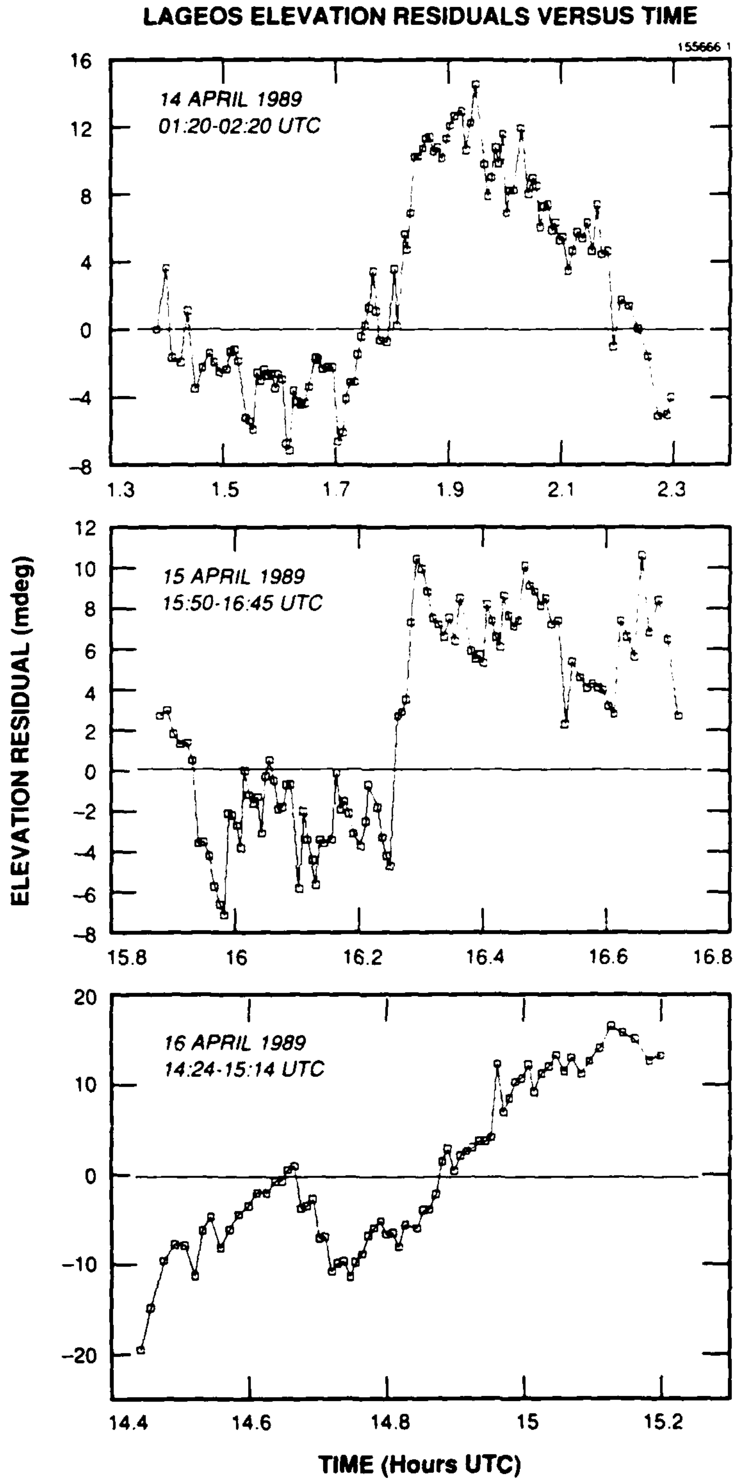


Figure 1-1. The elevation jump phenomenon.

2. ANGLE CALIBRATION MODELS

2.1 Determination of Model Parameters

To study the azimuth and elevation calibration model parameters, the FORTRAN program AZLCAL was written. AZLCAL is based on the program ERRMOD [3], but with several changes and improvements. The purpose of the program AZLCAL is to determine the optimal parameters for a given calibration model (azimuth or elevation) for a particular set of input data. The required input consists of one or more DYNAMO punch files containing azimuth and elevation residuals, and the parameters of the calibration models applied by SATCIT to those residuals. AZLCAL removes from the DYNAMO residuals the calibration correction applied by SATCIT at the time of data acquisition and does a least squares fit on the resulting raw residuals to determine new calibration model parameters. It produces an output file containing the new parameters and information about the fit, and updates a new calibration model database file with the newly determined parameters. This can be a previously existing or a new file. A history of the calibration model parameters applied by SATCIT are given in Appendix A. More detailed descriptions of the calibration models are given in [3] and [4].

The following angle calibration models are used in AZLCAL:

1. Azimuth axis/rail model:

$$
\begin{aligned}
daz_{corrected} &= daz_{raw} - BIAS - SKEW * tan(el) + \frac{COLL}{cos(el)} \\
&\quad + SLOPE(i) * az + INT(i)
\end{aligned}
$$

where $i = 1, 2, \ldots 8$ and

- $daz_{corrected}$ is the corrected azimuth residual $(mdeg)$
- daz_{raw} is the uncorrected azimuth residual $(mdeg)$
- $BIAS$ is the azimuth bias parameter $(mdeg)$
- $SKEW$ is the skew parameter $(mdeg)$
- $COLL$ is the collimation parameter $(mdeg)$
- $SLOPE(i)$ is the slope parameter for the ith rail $(mdeg/deg)$
- $INT(i)$ is the intercept parameter for the ith rail $(mdeg)$
- el is the observation elevation (deg)
- az is the observation azimuth (deg).

Note that in the equation above there are eight rail biases (the intercepts) as well as an overall bias term. These constant terms are related as follows. AZLCAL calculates eight rail intercept terms $INT'(i)$, where $i = 1, 2, \ldots 8$ indicates the rail number. The overall azimuth bias is defined to be the mean of these eight terms, with a change of sign:

$$BIAS = -\frac{1}{8}\sum_{i=1}^{8} INT'(i).$$

The change of sign is applied since the bias and intercept terms have opposite sign as defined in the model equation. The final intercept terms are defined to be the original intercept terms minus this mean:

$$INT(i) = INT'(i) - \frac{1}{8}\sum_{i=1}^{8} INT'(i).$$

2. Elevation model:

$$del_{corrected} = del_{raw} - BIAS - B * el - C * el^2$$

where

- $del_{corrected}$ is the corrected elevation residual ($mdeg$)
- del_{raw} is the uncorrected elevation residual ($mdeg$)
- $BIAS$ is the elevation bias parameter ($mdeg$)
- B is the linear model parameter ($mdeg/deg$)
- C is the quadratic model parameter ($mdeg/deg^2$)
- el is the observation elevation (deg).

AZLCAL contains options to suppress the B and C terms to produce a bias-only or a linear model. Because it has been shown [4] that the quadratic term is important, all elevation modeling done in this study used the full quadratic elevation model. AZLCAL also has the ability to solve for the elevation parameters using only data for which the satellite is rising in elevation, or only data for which the satellite is falling in elevation.

2.2 Time Variation of Model Parameters

The first application of AZLCAL was a study of the variation of the calibration model parameters over time. Several sets of data, each including observations over a four-week period, were collected to cover a time span of about one year. (A dataset thus consists of four consecutive DYNAMO punch files.) The datasets are identified by the modified Julian date (MJD) of the first punch file in the set. Each dataset was input to AZLCAL to determine a new set of parameters for the azimuth and the elevation calibration models. The solution parameters for each model were then plotted as a function of time. This was done for Lageos and for EGP. The plots for the period December 1988 through December 1989 are shown in Appendices B through E. (The error bars indicate one-sigma values.) Summaries are given in Tables 2-1 through 2-6. For both satellites, significant variation is seen in both the azimuth and elevation model parameters. No seasonal variation is apparent. The amount of variation seen suggests that more frequent updating of the model parameters might be useful.

To see how the model parameters would vary if the datasets contained overlapping data, two more sets of AZLCAL solutions, one for Lageos and one for EGP, were produced. Here again the input datasets consisted of four consecutive punch files. However, each dataset is offset from the next by only one week, so that each set is composed of three punch files contained in the preceding set, plus one new one. This was done for the period 17 March to 14 May 1989. The solutions obtained, for both satellites, are very similar to those obtained with the separated four-week datasets. This implies that updates of the model parameters could be made more frequently than once every four weeks. Thus, if desired, updates of the model parameters could be made as a part of the weekly calibration fit procedure.

2.3 Method and Frequency of Model Parameter Updates

To study the effects of updating the calibration models more frequently than is currently done, the program APPMDL was written. APPMDL removes the SATCIT-applied calibration model from a set of data (punch file residuals) and applies to those data a different model. The input consists of DYNAMO punch files, and a model file which contains the parameters of both the calibration model to be removed from the punch file residuals and those of the calibration model to be applied. It outputs a file containing the original (input) residuals and the newly determined residuals, with their mean and standard deviation.

The first test performed using APPMDL was to compare the original residuals from a given punch file to the residuals which would have resulted if a more recently determined calibration model had been used. To do this, five consecutive punch files were used. The first four were input to AZLCAL to produce the new azimuth and elevation model parameters. Then, APPMDL was used to remove the SATCIT-applied models from the residuals in the fifth punch file, and apply to them the new models determined by AZLCAL. This was done for two separate input datasets, for both Lageos and EGP. Summaries are given in Tables 2-7, 2-8, and 2-9. The new model gives residuals which are much closer to zero mean than the original residuals, as expected. The scatter,

however, is not significantly reduced. Figure 2-1 shows representative plots of the original and newly determined residuals for comparison. The first plot shows the residuals as corrected by SATCIT (input punch file date is 47525); the second plot shows the same residuals after removing the model applied by SATCIT and applying the model determined from the four punch files starting at MJD 47497. It is easily seen that the latter residuals are much closer to being unbiased than the former. Since unbiased residuals are one of the goals of calibration, it seems that more frequent, perhaps monthly, updates of the calibration model parameters would be useful in keeping the angle residuals unbiased.

In the testing just described, the satellites were treated completely independently; that is, Lageos data were used to create a model, which was then applied to Lageos data, and EGP data were used to create a model, which was then applied to EGP data. The question arose as to whether a model which was determined using data from both satellites would prove useful. AZLCAL was used to create such a joint model. Plots of the resulting model parameters are shown in Appendices F and G. The joint parameters are not significantly different than those determined for the individual satellites. The error bars are smaller, since more input data were used to determine the model parameters.

APPMDL was then used to apply the joint model to Lageos and EGP residuals. The same five-week method was used as described above. Lastly, APPMDL was used to apply the model determined from Lageos data to EGP residuals. Tables 2-7, 2-8, and 2-9 also summarize these APPMDL runs.

The output from each APPMDL run includes the mean and error (standard deviation) of the original residuals and the newly determined residuals. To determine the accuracy of the metrics obtainable with monthly model parameter updates, five APPMDL runs were made, each having four weeks of input data (four punch files). The accuracy of a metric (azimuth or elevation) can be characterized by the mean over these five runs of the mean residual, and the standard deviation of this mean. The associated precision (noise) can be characterized by the mean over the five runs of the APPMDL errors. The results of such calculations are shown in Table 2-10. These results imply that we can achieve an accuracy of 0.6 ± 0.9 mdeg in azimuth, with a precision of 10.7 mdeg, and an accuracy of 0.06 ± 1.0 mdeg in elevation, with a precision of 8.0 mdeg.

TABLE 2-1.

AZLCAL Calibration Model Parameter Summary: Lageos Azimuth Model

Parameter	Mean	Std Dev	Average Err Bar	Units
Azimuth bias	-25.712	11[illegible]	2.173	*mdeg*
Skew	7.992	7.[illegible]	1.650	*mdeg*
Coll	-9.002	10.571	0.417	*mdeg*
Slope				
Rail 1	0.126	0.070	0.096	*mdeg/deg*
2	0.076	0.138	0.061	*mdeg/deg*
3	0.130	0.217	0.062	*mdeg/deg*
4	0.104	0.076	0.068	*mdeg/deg*
5	0.075	0.119	0.078	*mdeg/deg*
6	0.186	0.070	0.053	*mdeg/deg*
7	0.388	0.062	0.040	*mdeg/deg*
8	0.011	0.073	0.030	*mdeg/deg*
Intercept				
Rail 1	17.898	8.440	3.709	*mdeg*
2	24.544	17.544	5.484	*mdeg*
3	-1.388	25.522	7.955	*mdeg*
4	-4.588	14.610	11.535	*mdeg*
5	-2.858	29.328	17.028	*mdeg*
6	-33.098	18.916	13.979	*mdeg*
7	-96.451	20.387	11.949	*mdeg*
8	26.069	24.312	10.806	*mdeg*

Notes:

Mean: The mean of the quantity over the 14 AZLCAL fits spanning the time period.

Std Dev: The standard deviation about the mean of the quantity over the 14 AZLCAL fits spanning the time period.

Average Err Bar: The mean of the 14 standard deviations from the AZLCAL fits spanning the time period.

See Appendix A to compare these values to those applied by SATCIT. (Certain SATCIT parameters remain constant over the time period, while others do not.)

TABLE 2-2.

AZLCAL Calibration Model Parameter Summary: Lageos Elevation Model

Parameter	Mean	Std Dev	Average Err Bar	Units
I. Solution Using All Data				
El bias	35.993	6.126	1.332	$mdeg$
b	0.084	0.180	0.050	$mdeg/deg$
c	-0.0040	0.0015	0.0005	$mdeg/deg^2$
II. Solution Using Rising Elevation Data Only				
El bias	28.842	6.178	1.442	$mdeg$
b	0.144	0.182	0.055	$mdeg/deg$
c	-0.0044	0.0015	0.0006	$mdeg/deg^2$
III. Solution Using Falling Elevation Data Only				
El bias	37.609	5.890	1.371	$mdeg$
b	0.257	0.176	0.050	$mdeg/deg$
c	-0.0058	0.0017	0.0006	$mdeg/deg^2$

Notes:
Mean: The mean of the quantity over the 14 AZLCAL fits spanning the time period.
Std Dev: The standard deviation about the mean of the quantity over the 14 AZLCAL fits spanning the time period.
Average Err Bar: The mean of the 14 standard deviations from the AZLCAL fits spanning the time period.
See Appendix A to compare these values to those applied by SATCIT. (Certain SATCIT parameters remain constant over the time period, while others do not.)

TABLE 2-3.

AZLCAL Calibration Model Parameter Summary: EGP Azimuth Model

Parameter	Mean	Std Dev	Average Err Bar	Units
Azimuth bias	-25.418	10.689	3.546	*mdeg*
Skew	9.766	6.599	1.686	*mdeg*
Coll	-5.941	11.455	1.222	*mdeg*
Rail 1	0.062	0.204	0.242	*mdeg/deg*
2	0.035	0.135	0.098	*mdeg/deg*
3	0.136	0.230	0.098	*mdeg/deg*
4	0.134	0.138	0.084	*mdeg/deg*
5	0.069	0.149	0.114	*mdeg/deg*
6	0.248	0.115	0.067	*mdeg/deg*
7	0.213	0.143	0.106	*mdeg/deg*
8	-0.028	0.206	0.103	*mdeg/deg*
Intercept				
Rail 1	18.775	18.021	10.476	*mdeg*
2	24.182	13.389	7.972	*mdeg*
3	-6.609	31.900	12.630	*mdeg*
4	-14.790	29.475	14.295	*mdeg*
5	-5.779	33.067	24.612	*mdeg*
6	-52.523	34.132	16.870	*mdeg*
7	-43.127	44.194	32.278	*mdeg*
8	50.875	74.110	37.446	*mdeg*

Notes:
Mean: The mean of the quantity over the 14 AZLCAL fits spanning the time period.
Std Dev: The standard deviation about the mean of the quantity over the 14 AZLCAL fits spanning the time period.
Average Err Bar: The mean of the 14 standard deviations from the AZLCAL fits spanning the time period.
See Appendix A to compare these values to those applied by SATCIT. (Certain SATCIT parameters remain constant over the time period, while others do not.)

TABLE 2-4.

AZLCAL Calibration Model Parameter Summary: EGP Elevation Model

Parameter	Mean	Std Dev	Average Err Bar	Units
I. Solution Using All Data				
El bias	36.877	4.597	1.661	*mdeg*
b	0.052	0.182	0.051	*mdeg/deg*
c	-0.0040	0.0022	0.0007	$mdeg/deg^2$
II. Solution Using Rising Elevation Data Only				
El bias	31.767	3.956	1.748	*mdeg*
b	0.046	0.183	0.056	*mdeg/deg*
c	-0.0046	0.0026	0.0007	$mdeg/deg^2$
III. Solution Using Falling Elevation Data Only				
El bias	39.418	5.394	1.862	*mdeg*
b	0.186	0.236	0.054	*mdeg/deg*
c	-0.0046	0.0029	0.0008	$mdeg/deg^2$

Notes:
Mean: The mean of the quantity over the 14 AZLCAL fits spanning the time period.
Std Dev: The standard deviation about the mean of the quantity over the 14 AZLCAL fits spanning the time period.
Average Err Bar: The mean of the 14 standard deviations from the AZLCAL fits spanning the time period.
See Appendix A to compare these values to those applied by SATCIT. (Certain SATCIT parameters remain constant over the time period, while others do not.)

TABLE 2-5.

AZLCAL Calibration Model Parameter Summary: Lageos + EGP Joint Azimuth Model

Parameter	Mean	Std Dev	Average Err Bar	Units
Azimuth bias	-29.643	9.525	1.329	*mdeg*
Skew	6.668	4.669	1.102	*mdeg*
Coll	-10.267	6.714	0.425	*mdeg*
Slope				
Rail 1	0.105	0.097	0.046	*mdeg/deg*
2	0.036	0.092	0.050	*mdeg/deg*
3	0.143	0.204	0.045	*mdeg/deg*
4	0.118	0.069	0.048	*mdeg/deg*
5	0.100	0.088	0.044	*mdeg/deg*
6	0.216	0.080	0.047	*mdeg/deg*
7	0.336	0.072	0.029	*mdeg/deg*
8	0.001	0.072	0.030	*mdeg/deg*
Intercept				
Rail 1	15.342	6.543	1.725	*mdeg*
2	23.805	9.036	4.191	*mdeg*
3	-7.320	25.028	5.682	*mdeg*
4	-11.139	14.527	8.170	*mdeg*
5	-12.990	20.935	9.369	*mdeg*
6	-44.061	21.964	12.007	*mdeg*
7	-82.598	21.691	8.942	*mdeg*
8	27.887	24.261	10.975	*mdeg*

Notes:
Mean: The mean of the quantity over the 14 AZLCAL fits spanning the time period.
Std Dev: The standard deviation about the mean of the quantity over the 14 AZLCAL fits spanning the time period.
Average Err Bar: The mean of the 14 standard deviations from the AZLCAL fits spanning the time period.
See Appendix A to compare these values to those applied by SATCIT. (Certain SATCIT parameters remain constant over the time period, while others do not.)

TABLE 2-6.

AZLCAL Calibration Model Parameter Summary: Lageos + EGP Joint Elevation Model

I. Solution Using All Data				
Parameter	Mean	Std Dev	Average Err Bar	Units
El bias	36.768	4.135	0.929	*mdeg*
b	0.048	0.127	0.033	*mdeg/deg*
c	-0.0037	0.0012	0.0004	$mdeg/deg^2$
II. Solution Using Rising Elevation Data Only				
El bias	30.740	3.386	1.018	*mdeg*
b	0.058	0.107	0.036	*mdeg/deg*
c	-0.0038	0.0010	0.0004	$mdeg/deg^2$
III. Solution Using Falling Elevation Data Only				
El bias	39.386	4.859	1.000	*mdeg*
b	0.181	0.186	0.034	*mdeg/deg*
c	-0.0050	0.0021	0.0004	$mdeg/deg^2$

Notes:
Mean: The mean of the quantity over the 14 AZLCAL fits spanning the time period.
Std Dev: The standard deviation about the mean of the quantity over the 14 AZLCAL fits spanning the time period.
Average Err Bar: The mean of the 14 standard deviations from the AZLCAL fits spanning the time period.
See Appendix A to compare these values to those applied by SATCIT. (Certain SATCIT parameters remain constant over the time period, while others do not.)

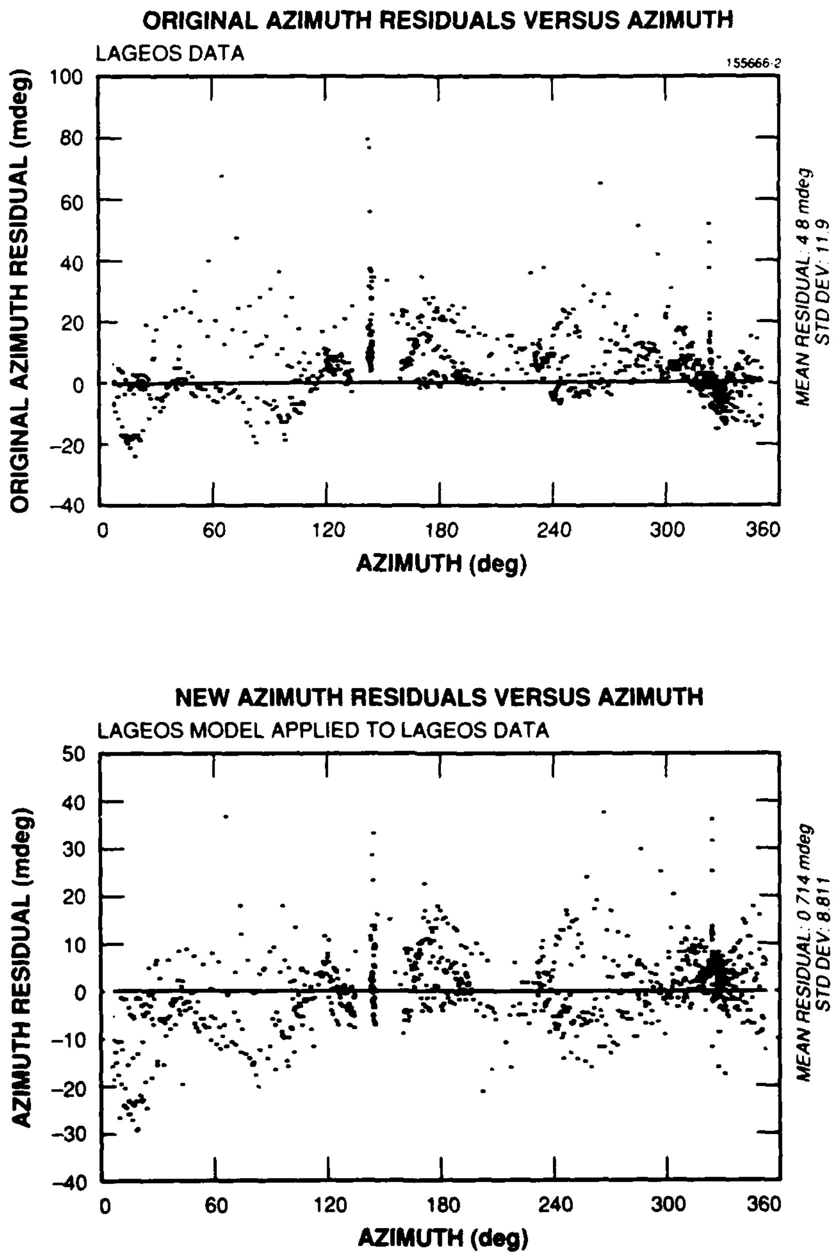


Figure 2-1. APPMDL results.

TABLE 2-7.

APPMDL Results: Azimuth

A. Input Punch File Date: 47525					
Sat	Orig Mean ($mdeg$)	Orig SD ($mdeg$)	New Mean ($mdeg$)	New SD ($mdeg$)	No. Obs
LL	4.8	11.9	0.714	8.811	933
JL	4.8	11.9	0.479	9.112	933
EE	2.3	10.3	-1.114	11.981	705
JE	2.3	10.3	-0.517	10.809	705
LE	2.3	10.3	0.578	10.854	705
B. Input Punch File Date: 47861					
LL	8.3	12.1	0.051	9.791	800
JL	8.3	12.1	0.431	10.127	800
EE	7.1	15.8	0.823	14.502	304
JE	7.1	15.8	2.369	13.623	304
LE	7.1	15.8	1.646	13.809	304

Key

LL: Model determined with Lageos data applied to Lageos residuals

JL: Model determined with joint data applied to Lageos residuals

EE: Model determined with EGP data applied to EGP residuals

JE: Model determined with joint data applied to EGP residuals

LE: Model determined with Lageos data applied to EGP residuals

TABLE 2-8.

APPMDL Results: Elevation: Punch File Date: 47525

1. Data Used: All					
Sat	Orig Mean ($mdeg$)	Orig SD ($mdeg$)	New Mean ($mdeg$)	New SD ($mdeg$)	No. Obs
LL	0.2	7.0	-0.522	6.613	933
JL	0.2	7.0	-1.024	6.630	933
EE	-2.4	10.3	-3.378	9.649	705
JE	-2.4	10.3	-2.405	9.801	705
LE	-2.4	10.3	-1.458	9.884	705
2. Data Used: Rising Elevation Only					
LL	-4.0	5.6	-0.284	5.225	421
JL	-4.0	5.6	-0.527	5.245	421
EE	-12.4	6.4	-8.108	5.313	280
JE	-12.4	6.4	-7.595	5.802	280
LE	-12.4	6.4	-6.743	6.019	280
3. Data Used: Falling Elevation Only					
LL	3.6	6.1	-1.794	5.345	512
JL	3.6	6.1	-2.192	5.356	512
EE	4.3	6.2	0 747	5.005	425
JE	4.3	6.2	-0.058	4.877	425
LE	4.3	6.2	0.394	4.874	425

Key

LL: Model determined with Lageos data applied to Lageos residuals

JL: Model determined with joint data applied to Lageos residuals

EE: Model determined with EGP data applied to EGP residuals

JE: Model determined with joint data applied to EGP residuals

LE: Model determined with Lageos data applied to EGP residuals

TABLE 2-9.

APPMDL Results: Elevation: Input Punch File Date: 47861

Sat	Orig Mean (*mdeg*)	Orig SD (*mdeg*)	New Mean (*mdeg*)	New SD (*mdeg*)	No. Obs
1. Data Used: All					
LL	-1.0	9.8	0.220	9.502	800
JL	-1.0	9.8	-0.595	9.406	800
EE	-5.7	14.0	-7.596	14.061	304
JE	-5.7	14.0	-5.952	13.847	304
LE	-5.7	14.0	-4.953	13.953	304
2. Data Used: Rising Elevation Only					
LL	-9.2	4.4	-2.325	4.417	371
JL	-9.2	4.4	-2.440	4.442	371
EE	-13.8	14.3	-7.734	12.583	143
JE	-13.8	14.3	-7.876	13.867	143
LE	-13.8	14.3	-7.472	14.141	143
3. Data Used: Falling Elevation Only					
LL	6.0	7.3	1.422	7.177	429
JL	6.0	7.3	-0.090	7.097	429
EE	1.4	8.9	-8.130	8.908	161
JE	1.4	8.9	-5.008	9.251	161
LE	1.4	8.9	-3.402	9.145	161

Key

LL: Model determined with Lageos data applied to Lageos residuals

JL: Model determined with joint data applied to Lageos residuals

EE: Model determined with EGP data applied to EGP residuals

JE: Model determined with joint data applied to EGP residuals

LE: Model determined with Lageos data applied to EGP residuals

TABLE 2-10.

Estimates of Metric Accuracy

Metric	Mean (*mdeg*)	SD (*mdeg*)	<SD> (*mdeg*)
Original azimuth	3.98	0.74	12.14
Updated azimuth	-0.57	0.92	10.67
Original elevation	0.78	1.17	8.06
Updated elevation	-0.06	1.05	8.03

2.4 Comparison of AZLCAL and Current Method

As a final test of the AZLCAL model parameter calculations, a comparison was made between the azimuth rail model parameters calculated using AZLCAL and those derived using the existing method. The existing method for updating model parameters will be described, and the results of the comparisons presented.

Currently, monitoring and updating the calibration models is performed by Janusz Sciegienny of Group 91, as described in References 4 and 5. This method treats the azimuth rail model independent of azimuth bias, skew, and collimation. (The skew and collimation terms have not been changed in many years. Azimuth bias updates are made when the azimuth bias becomes larger than a predetermined value.) Like AZLCAL, this method uses DYNAMO punch files as input. These files are processed using a set of FORTRAN programs which collect the azimuth residuals in 5-deg azimuth bins. Screening the residuals is based on DYNAMO screening methods, in the same way as is done in AZLCAL. The binned azimuth residuals are averaged, and a plot is produced which shows the averaged residuals versus azimuth. Figure 2-2 contains an example of such a plot. The error bars are one-sigma values.

A hardcopy of this plot is made, and the values of the averaged azimuth residuals are determined by measurement with a ruler. Because each rail covers 45 deg in azimuth, there are 9 such values per rail. These values are input to Lotus 1-2-3 on a PC, and a linear regression on these data is performed for each rail to determine the new model parameters.

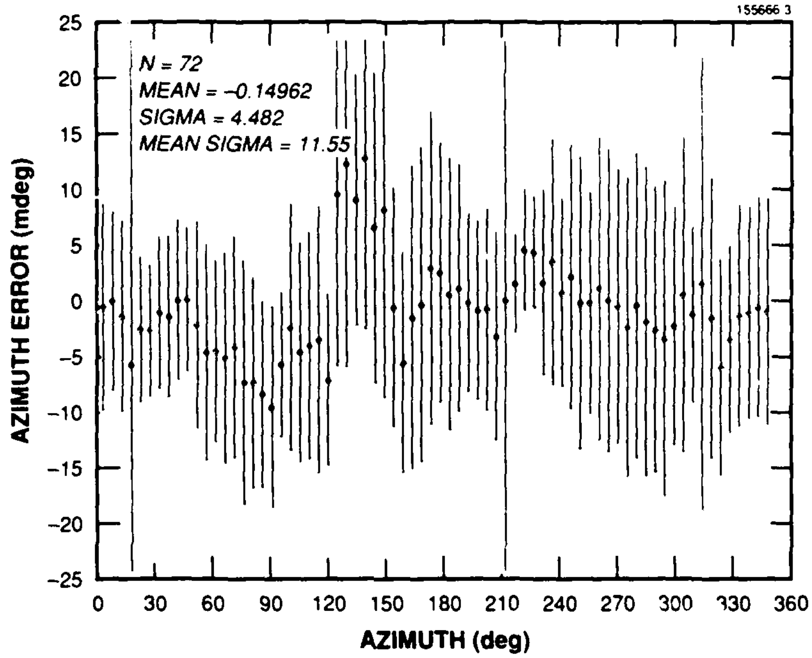
Aside from the incomplete automation of this method, there are two important differences from the AZLCAL method. First, the solution parameters determined by the existing method are corrections to the SATCIT-applied parameters, because the SATCIT-applied parameters are not removed from the residuals before they are processed. Second, no weights are applied to the data prior to the linear regression, i.e., the method uses azimuth angle errors, not traverse errors. The monopulse feed system of the Millstone radar causes an azimuth error accuracy that is proportional to the reciprocal of the cosine of the elevation $[1/cos(el)]$. Thus, higher elevation data have a greater azimuth error. AZLCAL accordingly weights the data by $1/cos(el)$ before performing the least squares solution. This is equivalent to using traverse errors instead of azimuth errors. (Note that the unweighted data are subject to a somewhat similar natural weighting because there is more spatial volume at low elevation than at high elevation). The question arises as to whether the model parameters should be determined using weighted or unweighted data.

To try to resolve this issue, a new version of AZLCAL was written which provided two new options. First, the user may choose whether or not to remove the SATCIT-applied model from the residuals. Thus, either corrections to the existing model parameters, or new parameters, may be determined. Second, the user may choose to weight the data by $1/cos(el)$ prior to the least-squares solution, or not to weight the data. Two sets of comparisons were then made. For each set, three rail model parameter solutions were determined: (1) using the existing manual method; (2) using AZLCAL to determine a correction to the SATCIT-applied parameters using unweighted data; and (3) using AZLCAL to determine a correction to the SATCIT-applied parameters using weighted data. The first dataset covers the time period 29 December 1989 to 26 February 1990; the second

dataset covers the time period 17 May to 13 November 1989. An update to the rail model was made on 13 December 1989, so that the corrections determined from these two datasets do not apply to the same parameters. The results are shown in Tables 2-11 and 2-12. The unweighted AZLCAL solution produces similar results to the existing method. The differences are due to the existing method's averaging of the azimuth error at 5-deg increments and its partly manual nature.

The AZLCAL weighted and unweighted solutions are rather different in detail. Which is the "better" solution? Tables 2-13 through 2-16 show individual rail statistics and total system statistics for the two sets of AZLCAL solutions. Consider, for example, the second dataset. The unweighted solution shows a prefit standard deviation of 13.66 mdeg for the system as a whole, and a postfit standard deviation of 12.38 mdeg. The weighted solution has a prefit standard deviation of 5.92 mdeg and a postfit standard deviation of 4.94 mdeg. The improvements are very similar in each case. Rail 5, for example, has an unweighted prefit standard deviation of 13.95 mdeg and an unweighted postfit standard deviation of 13.76 mdeg; it has a weighted prefit standard deviation of 5.62 mdeg, and a weighted postfit standard deviation of 5.36 mdeg. Again, the improvements are very similar. The first dataset also shows comparable results. Thus, the choice of method (weighted or unweighted solution) is not clearly determined by these statistics.

However, investigation of several satellite passes in the DYNAMO punch files shows that very large azimuth errors often occur for observations at high elevations. For an example, see Figure 2-3, which contains a partial Lageos pass from a DYNAMO punch file. As the elevation (ELEV) becomes greater than 75 deg, the azimuth residual (DAZ) increases from a few to tens of millidegrees. The azimuth residuals drop to a few millidegrees again after the satellite has fallen below about 75-deg elevation. A weighted solution would then be preferred, in order to prevent such data points from skewing the model parameter solution.



SATELLITE 8820
MILLSTONE MH 369
29 DECEMBER 1989 THROUGH
26 FEBRUARY 1990

Figure 2-2. Sample azimuth error plot (current method).

OBJECT: 8820
YYDDD: 90 70
PASS: 615369

YYMMDD	HHMMSS	AZIM DEG	ELEV DEG	RANGE KM	RANGE-RATE M/S	DAZ MDEG	DEL MDEG	DRNG M	DRR MM/S
90 311	132534.	146.3	33.7	7549.0	-2578.711	4.3	-5.1	5.86	3.0
90 311	132559.	146.4	34.8	7484.6	-2546.113	3.4	-1.4	6.23	4.5X
90 311	132624.	146.5	35.9	7420.2	-2511.794	2.2	-5.8	5.88	4.5X
90 311	132649.	146.6	36.9	7357.5	-2476.617	-1.2	-2.7	5.08	4.6X
90 311	132740.	146.8	39.1	7233.1	-2401.452	-1.2	-4.5	5.33	4.3X
90 311	1328 6.	146.8	40.3	7173.3	-2362.447	-1.7	-3.8	5.39	3.4X
90 311	132830.	146.9	41.3	7116.3	-2323.387	-0.9	-4.5	5.80	2.8X
90 311	132857.	147.0	42.6	7052.8	-2277.546	0.2	-5.2	5.58	1.3
90 311	132923.	147.1	43.7	6995.3	-2233.730	4.2	-4.8	5.67	0.3
90 311	133013.	147.4	46.1	6885.1	-2143.049	7.2	-1.2	5.21	-0.5
90 311	133038.	147.5	47.3	6831.7	-2095.602	5.5	-5.0	5.26	-0.3
90 311	1331 4.	147.6	48.5	6779.7	-2046.797	0.6	-5.2	5.67	-0.5
90 311	133129.	147.7	49.7	6728.7	-1996.450	0.9	-4.0	5.87	0.1
90 311	133155.	147.8	51.0	6677.0	-1942.421	0.4	-3.4	5.95	0.6
90 311	133220.	148.0	52.2	6628.9	-1889.406	2.3	-4.2	5.36	1.0
90 311	133310.	148.3	54.7	6536.8	-1778.994	2.7	-5.3	5.60	0.3
90 311	133335.	148.4	56.0	6492.9	-1721.809	2.3	-2.7	5.14	0.2
90 311	1334 0.	148.6	57.3	6450.5	-1663.233	2.4	-3.2	5.17	0.0
90 311	133426.	148.7	58.6	6409.5	-1603.136	4.6	-3.6	5.04	0.5
90 311	133451.	148.9	59.9	6370.2	-1541.897	5.7	-1.9	4.89	0.2
90 311	133541.	149.3	62.5	6295.9	-1415.061	1.1	-2.1	4.90	0.3
90 311	1336 7.	149.5	63.9	6259.9	-1346.979	2.3	0.0	5.62	0.7
90 311	133641.	149.9	65.7	6215.2	-1255.591	0.9	0.3	5.20	1.7
90 311	133658.	150.1	66.7	6194.2	-1209.260	-0.2	0.1	5.25	1.0
90 311	133733.	150.5	68.6	6154.1	-1114.077	4.4	-0.4	4.73	1.0
90 311	1338 7.	151.0	70.4	6117.8	-1017.940	4.5	0.3	4.73	1.1
90 311	133841.	151.5	72.3	6084.6	-919.224	2.5	-1.9	4.51	0.8
90 311	133858.	151.8	73.3	6069.4	-869.725	0.0	-2.0	4.69	0.7
90 311	133929.	152.5	75.0	6044.2	-779.770	-2.5	-1.6	4.48	1.2
90 311	133956.	153.2	76.5	6024.1	-698.529	15.1	-1.7	4.91	0.7
90 311	134036.	154.6	78.8	5998.7	-578.235	26.9	-4.9	4.62	0.2
90 311	1341 2.	155.8	80.3	5984.5	-497.905	19.6	-3.9	4.71	0.0
90 311	134128.	157.5	81.8	5972.6	-417.647	17.3	-4.3	4.62	0.0
90 311	134158.	160.3	83.5	5961.5	-324.524	33.3	-3.0	4.90	0.4
90 311	134225.	164.3	84.9	5954.0	-242.056	20.0	-7.6	4.87	0.4
90 311	1343 4.	177.6	87.1	5946.8	-117.646	-196.1X	-0.5	4.66	0.6
90 311	134331.	203.1	88.2	5944.8	-34.793	-850.2X	-1.8	4.86	0.2
90 311	1344 8.	275.0	88.2	5945.6	80.363	-222.1	7.7	4.12	0.4
90 311	134434.	298.6	87.0	5948.8	162.401	240.8	15.6	4.22	0.5
90 311	1345 0.	308.4	85.6	5954.2	244.477	36.0	14.5	4.20	0.5
90 311	134526.	313.4	84.1	5961.6	325.930	85.9	8.6	4.15	0.3
90 311	1346 6.	317.6	81.9	5976.9	447.388	65.3	8.7	4.21	-0.2
90 311	134632.	319.3	80.4	5989.7	527.645	50.7	8.8	4.24	0.2
90 311	134658.	320.6	79.0	6004.6	607.039	37.3	8.8	4.29	0.2
90 311	134725.	321.6	77.5	6021.6	685.845	28.7	8.7	4.44	0.4
90 311	1348 4.	322.7	75.3	6050.9	802.335	5.1	12.1	3.80	0.3
90 311	134830.	323.3	73.8	6073.0	878.937	8.3	12.0	3.68	0.1
90 311	1349 1.	323.9	72.1	6100.8	965.503	4.0	11.9	3.98	0.8
90 311	134934.	324.5	70.2	6135.3	1061.122	-1.3	11.3	4.14	-0.2
90 311	1350 9.	324.9	68.4	6173.3	1155.615	-1.2	10.9	4.57	-0.2
90 311	135026.	325.2	67.4	6193.4	1201.926	-1.2	10.8	4.10	-0.1
90 311	135060.	325.6	65.6	6235.8	1292.227	-3.5	10.1	4.43	0.5
90 311	135134.	325.9	63.8	6281.3	1380.530	-2.3	12.8	4.43	0.5
90 311	1352 8.	326.2	62.0	6330.3	1467.172	-8.3	13.3	3.97	0.4
90 311	135225.	326.4	61.1	6355.8	1509.405	-2.5	12.6	3.98	0.8

Figure 2-3. Example of satellite pass from DYNAMO punch file.

TABLE 2-11.

AZLCAL/Current Method Comparison: Model Parameter Solutions: Dataset 1

	Existing Method		Unweighted AZLCAL		Weighted AZLCAL		
	Parameter	Sigma	Parameter	Sigma	Parameter	Sigma	Units
Slope 1	- 0.13	0.04	-0.0875	0.0384	-0.0752	0.0257	*mdeg*
Int 1	4.94	1.36	3.3585	1.8585	2.2218	1.2193	*mdeg/deg*
Slope 2	0.14	0.05	0.0721	0.0523	0.0576	0.0339	*mdeg*
Int 2	-19.34	1.87	-12.5882	5.1265	-14.1074	3.2876	*mdeg/deg*
Slope 3	-0.13	0.21	-0.1661	0.0594	-0.1221	0.0325	*mdeg*
Int 3	23.82	8.26	27.1115	8.3147	15.4475	5.2580	*mdeg/deg*
Slope 4	-0.02	0.04	0.0571	0.0528	0.2228	0.0325	*mdeg*
Int 4	4.70	1.74	-9.5308	9.8893	-43.0858	6.0517	*mdeg/deg*
Slope 5	0.09	0.06	0.1030	0.0387	-0.0781	0.0255	*mdeg*
Int 5	18.78	2.42	-21.1597	9.0050	20.8651	5.9428	*mdeg/deg*
Slope 6	-0.07	0.03	-0.0685	0.0439	-0.1032	0.0299	*mdeg*
Int 6	19.97	1.06	19.6383	12.1986	25.0195	8.3208	*mdeg/deg*
Slope 7	-0.03	0.07	-0.0648	0.0366	0.0141	0.0241	*mdeg*
Int 7	8.36	2.59	20.6805	11.7443	-9.2460	7.7168	*mdeg/deg*
Slope 8	-0.08	0.04	-0.0888	0.0290	-0.0473	0.0196	*mdeg*
Int 8	28.68	1.54	32.7693	10.4802	16.2454	7.0416	*mdeg/deg*

TABLE 2-12.

AZLCAL/Current Method Comparison: Model Parameter Solutions: Dataset 2

	Existing Method		Unweighted AZLCAL		Weighted AZLCAL		
	Parameter	Sigma	Parameter	Sigma	Parameter	Sigma	Units
Slope 1	-0.0386	0.0400	0.0001	0.0240	0.0150	0.0131	*mdeg*
Int 1	10.9314	1.5536	9.3493	1.2204	7.3615	0.6504	*mdeg/deg*
Slope 2	-0.0183	0.0359	-0.0124	0.0320	-0.0796	0.0185	*mdeg*
Int2	1.0820	1.3887	0.2522	3.1269	4.3483	1.8078	*mdeg/deg*
Slope 3	-0.1022	0.0757	-0.2248	0.0297	-0.1836	0.0164	*mdeg*
Int 3	22.4188	2.9324	40.0182	4.1875	32.0128	2.2830	*mdeg/deg*
Slope 4	-0.1135	0.0191	-0.1063	0.0254	-0.0321	0.0142	*mdeg*
Int 4	23.8179	0.7415	22.5518	4.7613	7.6565	2.6368	*mdeg/deg*
Slope 5	0.0896	0.0611	0.0498	0.0295	-0.0339	0.0160	*mdeg*
Int 5	-19.3076	2.3647	-9.3720	6.8589	10.0390	3.7015	*mdeg/deg*
Slope 6	0.1013	0.0252	0.0894	0.0304	0.0182	0.0179	*mdeg*
Int 6	-19.4415	0.9775	-16.2600	8.4352	-0.0474	4.9676	*mdeg/deg*
Slope 7	-0.2850	0.0461	-0.2985	0.0248	-0.2413	0.0140	*mdeg*
Int 7	95.2979	1.7806	99.2633	7.9613	78.6231	4.4665	*mdeg/deg*
Slope 8	-0.0283	0.0284	-0.0520	0.0233	-0.0712	0.0132	*mdeg*
Int 8	13.4469	1.0985	22.5146	8.4589	29.7366	4.7408	*mdeg/deg*

TABLE 2-13.

AZLCAL/Current Method Comparison: Unweighted Statistics: Dataset 1

Rail Indicator	Original Data	Raw Data	Fitted Data	Key
1	537	537	537	(Data Points)
	-0.71	-0.71	0.00	(Mean: *mdeg*)
	7.83	7.83	7.71	(Error: *mdeg*)
2	303	303	303	(Data Points)
	-5.51	-5.51	0.00	(Mean: *mdeg*)
	11.63	11.63	10.20	(Error: *mdeg*)
3	220	220	220	(Data Points)
	2.85	2.85	0.00	(Mean: *mdeg*)
	15.07	15.07	14.63	(Error: *mdeg*)
4	329	329	329	(Data Points)
	1.22	1.22	0.00	(Mean: *mdeg*)
	12.26	12.26	12.17	(Error: *mdeg*)
5	608	608	608	(Data Points)
	2.82	2.82	0.00	(Mean: *mdeg*)
	14.32	14.32	13.98	(Error: *mdeg*)
6	474	474	474	(Data Points)
	0.62	0.62	0.00	(Mean: *mdeg*)
	14.06	14.06	14.02	(Error: *mdeg*)
7	717	717	717	(Data Points)
	-0.39	-0.39	0.00	(Mean: *mdeg*)
	14.67	14.67	14.65	(Error: *mdeg*)
8	932	932	932	(Data Points)
	-0.42	-0.42	0.00	(Mean: *mdeg*)
	8.38	8.38	8.29	(Error: *mdeg*)
System	4120	4120	4120	(Data Points)
	0.08	0.08	0.00	(Mean: *mdeg*)
	12.18	12.18	11.96	(Error: *mdeg*)

TABLE 2-14.

AZLCAL/Current Method Comparison: Weighted Statistics: Dataset 1

Rail Indicator	Original Data	Raw Data	Fitted Data	Key
1	537	537	537	(Data Points)
	-0.78	-0.78	0.11	(Mean: *mdeg*)
	5.30	5.30	5.17	(Error: *mdeg*)
2	303	303	303	(Data Points)
	-5.17	-5.17	0.76	(Mean: *mdeg*)
	8.71	8.71	6.14	(Error: *mdeg*)
3	220	220	220	(Data Points)
	-0.45	-0.45	1.22	(Mean: *mdeg*)
	7.35	7.35	7.02	(Error: *mdeg*)
4	329	329	329	(Data Points)
	-0.07	-0.07	0.65	(Mean: *mdeg*)
	7.53	7.53	7.18	(Error: *mdeg*)
5	608	608	608	(Data Points)
	2.13	2.13	0.17	(Mean: *mdeg*)
	5.25	5.25	4.79	(Error: *mdeg*)
6	474	474	474	(Data Points)
	-1.60	-1.60	0.91	(Mean: *mdeg*)
	6.64	6.64	6.03	(Error: *mdeg*)
7	717	717	717	(Data Points)
	-2.49	-2.49	1.01	(Mean: *mdeg*)
	7.19	7.19	6.20	(Error: *mdeg*)
8	932	932	932	(Data Points)
	-0.82	-0.82	0.26	(Mean: *mdeg*)
	5.36	5.36	5.21	(Error: *mdeg*)
System	4120	4120	4120	(Data Points)
	-1.00	-1.00	0.55	(Mean: *mdeg*)
	6.42	6.42	5.78	(Error: *mdeg*)

TABLE 2-15.

AZLCAL/Current Method Comparison: Unweighted Statistics: Dataset 2

Rail Indicator	Original Data	Raw Data	Fitted Data	Key
1	1574	1574	1574	(Data Points)
	9.35	9.35	0.00	(Mean: $mdeg$)
	13.77	13.77	10.10	(Error: $mdeg$)
2	880	880	880	(Data Points)
	-0.95	-0.95	0.00	(Mean: $mdeg$)
	14.98	14.98	14.95	(Error: $mdeg$)
3	1008	1008	1008	(Data Points)
	7.39	7.39	0.00	(Mean: $mdeg$)
	15.06	15.06	12.79	(Error: $mdeg$)
4	1351	1351	1351	(Data Points)
	2.64	2.64	0.00	(Mean: $mdeg$)
	15.53	15.53	15.24	(Error: $mdeg$)
5	1025	1025	1025	(Data Points)
	2.17	2.17	0.00	(Mean: $mdeg$)
	13.95	13.95	13.76	(Error: $mdeg$)
6	994	994	994	(Data Points)
	8.62	8.62	0.00	(Mean: $mdeg$)
	16.10	16.10	13.55	(Error: $mdeg$)
7	1867	1867	1867	(Data Points)
	2.34	2.34	0.00	(Mean: $mdeg$)
	10.54	10.54	9.68	(Error: $mdeg$)
8	1634	1634	1634	(Data Points)
	3.16	3.16	0.00	(Mean: $mdeg$)
	11.44	11.44	10.98	(Error: $mdeg$)
System	10333	10333	10333	(Data Points)
	4.38	4.38	0.00	(Mean: $mdeg$)
	13.66	13.66	12.38	(Error: $mdeg$)

TABLE 2-16.

AZLCAL/Current Method Comparison: Weighted Statistics: Dataset 2

Rail Indicator	Original Data	Raw Data	Fitted Data	Key
1	1574	1574	1574	(Data Points)
	6.01	6.01	0.32	(Mean: *mdeg*)
	7.49	7.49	4.59	(Error: *mdeg*)
2	880	880	880	(Data Points)
	-1.68	-1.68	0.51	(Mean: *mdeg*)
	5.36	5.36	4.79	(Error: *mdeg*)
3	1008	1008	1008	(Data Points)
	4.25	4.25	0.57	(Mean: *mdeg*)
	7.32	7.32	6.03	(Error: *mdeg*)
4	1351	1351	1351	(Data Points)
	1.38	1.38	0.22	(Mean: *mdeg*)
	4.88	4.88	4.71	(Error: *mdeg*)
5	1025	1025	1025	(Data Points)
	1.69	1.69	0.14	(Mean: *mdeg*)
	5.62	5.62	5.36	(Error: *mdeg*)
6	994	994	994	(Data Points)
	4.00	4.00	0.77	(Mean: *mdeg*)
	6.11	6.11	5.07	(Error: *mdeg*)
7	1867	1867	1867	(Data Points)
	0.68	0.68	0.55	(Mean: *mdeg*)
	5.13	5.13	4.73	(Error: *mdeg*)
8	1634	1634	1634	(Data Points)
	2.24	2.24	0.06	(Mean: *mdeg*)
	5.18	5.18	4.65	(Error: *mdeg*)
System	10333	10333	10333	(Data Points)
	2.40	2.40	0.37	(Mean: *mdeg*)
	5.92	5.92	4.94	(Error: *mdeg*)

3. THE ELEVATION JUMP PHENOMENON

3.1 AZLCAL Modeling

A trend is seen in the elevation residuals which has not yet been explained: a bias is seen between the residuals for which the satellite is rising in elevation and the residuals for which the satellite is falling in elevation. In order to try to model this phenomenon, AZLCAL was given the ability to solve for an elevation model using only rising or only falling elevation data. Such solutions were determined for Lageos, for EGP, and jointly using both Lageos and EGP. Plots of the resulting model parameters are shown in Appendices H through M. The model parameters found with only rising elevation data are somewhat different than those found with only falling elevation data. The parameters determined with only rising elevation data tend to be less than those determined with all the elevation data, and those determined with only falling elevation data tend to be greater than those determined with all the data. This is consistent with the jump phenomenon.

Residual testing with APPMDL was performed as described in Section 2.3, applying the new models created with only rising or only falling elevation data. Summaries are given in Tables 2-8 and 2-9. Dividing the elevation model into rising and falling pieces does show an ability to produce slightly better results. However, a new elevation model, with separate parameters for rising and falling elevation, does not seem to be the correct way to remove the elevation jump from the residuals, mainly because such a model may not apply to all satellites. For example, the elevation jump phenomenon is not seen in the residuals for Etalon.

Because elevation jump effect is seen for satellites with low to moderate altitudes (e.g., Lageos and EGP), but unseen for the high altitude satellite Etalon, the question of whether elevation rate could play a role was considered.

3.2 Elevation Rate Dependence

To study the effect of azimuth and elevation rate on the residuals, MDBPUN was written. This program matches the punch file data with the corresponding observation in the metric database (MDB) and calculates the azimuth and elevation rate between each observation. (The MDB data are needed because the observation time, azimuth, and elevation are not recorded to sufficient precision in the punch file.) Plots of azimuth residuals versus azimuth rates show no trends, as expected. Plots of elevation rates versus elevation residuals are shown in Appendix N. Each plot shows several different passes of a given satellite, and a cubic fit to all the data. The plots for Lageos and EGP do show the jump phenomenon, but in a somewhat inconsistent fashion; the individual passes do not show a uniform shape or jump size. There are many fewer data for Etalon than for the other satellites; no jump is seen. The final pair of plots shows data for Lageos, EGP and Etalon all on the same plot, with a joint cubic fit.

Attempts to model the jump have failed. A step function model seems inappropriate since the step size is satellite dependent. Linear fits to the data show no trend. The cubic fits are

also disappointing. The cubic fit equations are given in Table 3-1. The standard error before and after the fit were determined for each satellite individually and for the joint cubic. The resulting standard errors are shown in Table 3-2. The joint cubic does not give any better results than a fit done using data only for one satellite.

TABLE 3-1.

Cubic Fit Equations

Satellite	Constant ($mdeg$)	x ($mdeg/deg$)	x^2 ($mdeg/deg^2$)	x^3 ($mdeg/deg^3$)
Lageos	4.55	-5.75×10^{-2}	-2.01×10^{-5}	2.65×10^{-9}
EGP	8.44	-7.34×10^{-2}	-6.02×10^{-5}	6.38×10^{-7}
Etalon	2.86	-0.21×10^{-1}	-2.12×10^{-3}	5.05×10^{-6}
Joint	6.26	-5.81×10^{-2}	-2.02×10^{-5}	2.67×10^{-9}

TABLE 3-2.

Cubic Fit Comparisons

Satellite	Std Error Before Fit ($mdeg$)	Std Error Satellite ($mdeg$)	Std Error Combined ($mdeg$)
Lageos	9.850	8.031	8.173
EGP	12.402	7.096	7.377
Etalon	7.233	4.913	6.980

4. TILTMETER CALIBRATION

The last area of study was the tiltmeter calibration. Another factor which could possibly explain the elevation jump would be some problem with the tiltmeters, either mechanical or in their calibration. Tiltmeter data during five different Lageos passes, two at night and three during the day, were studied. Three programs were used. SATSNR, written by T. A. Cott of Group 91, was used to retrieve the tiltmeter data from raw SATCIT data tapes. The raw data contains azimuth tilt and elevation tilt values, each measured twice per second. To reproduce the correction that SATCIT applied to the metric observations, the program TLTAVG was used to average the raw tilt values over a period of twenty seconds centered on the punch file observation time, and the program TLTCOR was used to calculate the correction to each residual using the tiltmeter calibration models. The tiltmeter calibration models are given by:

Correction due to azimuth tiltmeter (also called the orthogonal or sine tiltmeter):

$$daz = -(V_2 - V_{2b}) * C_2 * tan(el)$$

where

- daz is the azimuth correction (deg)
- V_2 is the azimuth tiltmeter output voltage $(counts)$
- V_{2b} is the azimuth tiltmeter bias $(counts)$
- C_2 is the azimuth tiltmeter scale factor $(deg/count)$
- el is the observation elevation (deg).

Correction due to elevation tiltmeter (also called the principal or cosine tiltmeter):

$$del = (V_1 - V_{1b}) * C_1$$

where

- del is the elevation correction (deg)
- V_1 is the elevation tiltmeter output voltage $(counts)$
- V_{1b} is the elevation tiltmeter bias $(counts)$
- C_1 is the elevation tiltmeter scale factor $(deg/count)$

The raw tiltmeter data were plotted against time and against the corresponding metric (e.g., azimuth tilt versus azimuth). The correction due to each tiltmeter was then calculated and plotted against time, against the corresponding metric, and against the corresponding total residual (e.g., azimuth tilt correction versus total azimuth residual). Representative plots of the raw tiltmeter data and of the tiltmeter corrections are shown in Appendix O. Current calibration models appear to be performing well, and no relationship to the elevation jump phenomenon is seen.

5. RECOMMENDATIONS AND CONCLUSIONS

In summary, it is evident that the current angle calibration models are still effective, but more frequent updating of the model parameters on a monthly basis is recommended. To maximize the amount of data used, this recalibration should be done using both Lageos and EGP data. Use of a weighted solution to include the effect of the monopulse feed system is recommended. Regular updates using the program AZLCAL would be simple to perform; a user's guide to such a calibration procedure is being written. The accuracies attainable with such a procedure are estimated to be 0.6 ± 0.9 mdeg for azimuth, with a precision of 10.7 mdeg, and 0.1 ± 1.0 mdeg for elevation, with a precision of 8.0 mdeg (see Table 2-10).

No seasonal effects are seen in the variation of the model parameters for either azimuth or elevation. This is somewhat surprising, since the refraction model being used in SATCIT is known to be less than optimal. It is possible that the quadratic elevation model is masking a refraction effect.

Attempts to model the elevation jump phenomenon have as yet been unsuccessful. Rate dependent terms in the model do not appear to be necessary or useful. No effects from the tiltmeters have been seen. Further work will be needed to resolve the elevation jump phenomenon.

Current tiltmeter calibration models appear to be working well. No relationship is seen between the corrections due to the tiltmeters and the total residual for either azimuth or elevation.

REFERENCES

1. L.E. Thornton and A.L. Williams, private communication (25 October 1989).

2. J.V. Evans (ed.), *Millstone Hill Radar Propagation Study: Calibration*, MIT Lincoln Laboratory, Lexington, Mass., Technical Rep. 508, (5 October 1973). DTIC AD-779689.

3. E.M. Gaposchkin, R.M. Byers, and G.H. Conant, private communication (11 December 1986).

4. J. Sciegienny, private communication (21 December 1988).

5. J. Sciegienny and J. Knecht, private communication (17 September 1989).

APPENDIX A
SATCIT CALIBRATION MODEL PARAMETERS

```
D:OAZMDL

Last update: 4 January 1990

Contains azimuth model calibration values
Format is:

DATE       AZ (deg)  SKEW (deg)   COLL (deg)
  SLOPE1 SLOPE2 SLOPE3 SLOPE4 SLOPE5 SLOPE6 SLOPE7 SLOPE8 (mdeg/deg)
  INT1   INT2   INT3   INT4   INT5   INT6   INT7   INT8   (mdeg)
...............................................................................
46047    -0.045       -0.000333   -0.01600
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
46229    -0.045       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
46241    -0.045       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
46334    -0.051       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
46389    -0.051       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
46534    -0.051       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
46954    -0.051       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
47008    -0.051       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
47034    -0.051       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
47231    -0.051       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
47412    -0.051       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
47447    -0.051       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
47455    -0.054       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
47536    -0.054       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
47663    -0.054       -0.003694   -0.01853
 +0.0864   +0.0365   -0.0014   +0.0634   +0.0379   +0.2156   +0.1543   +0.0446
 +0.37     -0.84     -1.45    -18.79    -16.35    -61.76    -45.53    -10.33
47852    -0.054       -0.003694   -0.01853
 +0.0478   +0.0182   -0.1036   -0.0501   +0.1275   +0.3169   -0.1307   +0.0163
 +11.30    +0.24    +20.97     +5.03    -35.66    -81.20    +49.77     +3.12
```

Calibration Model Parameters Applied by SATCIT:

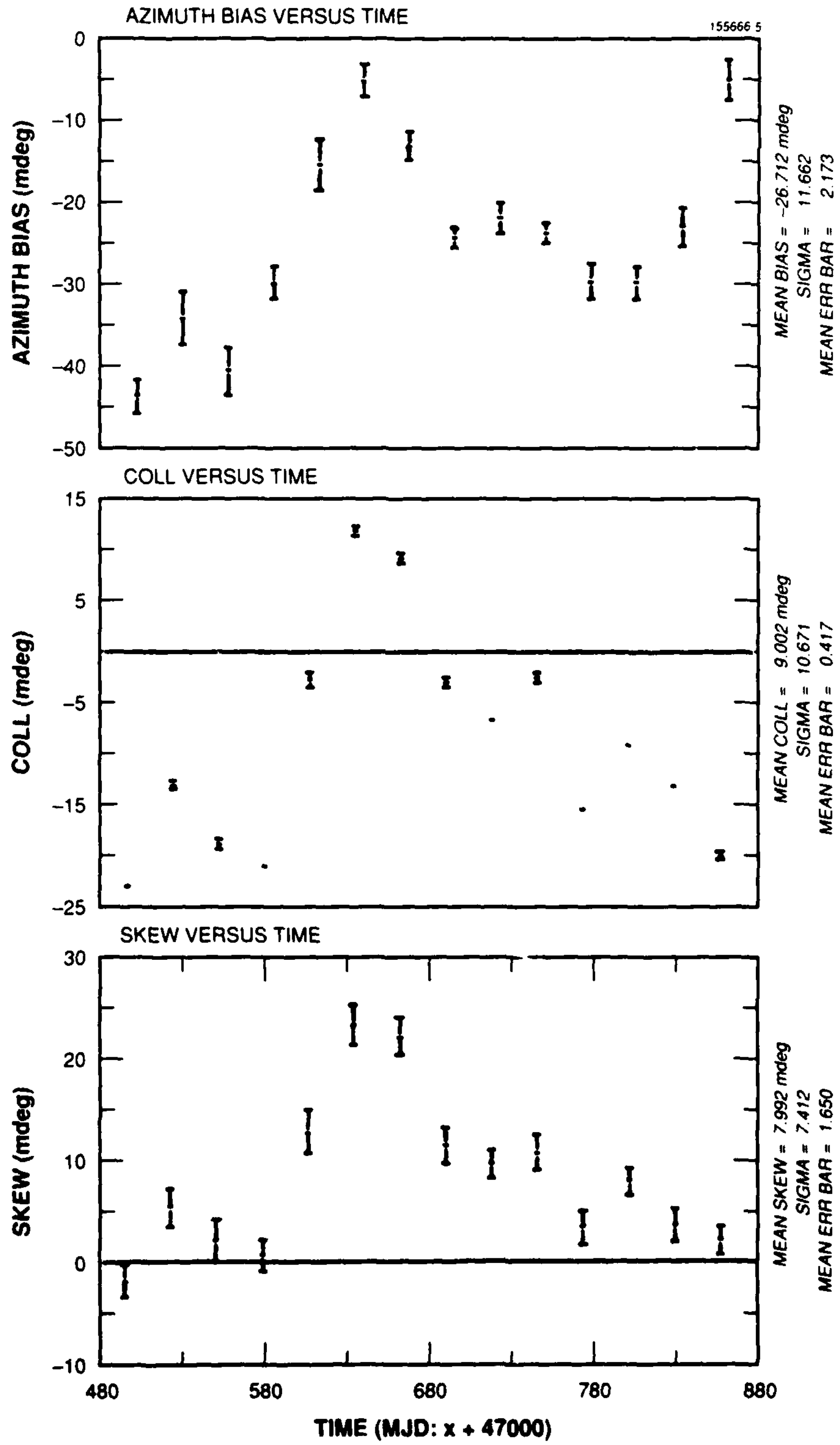
ELEVATION

Format is:

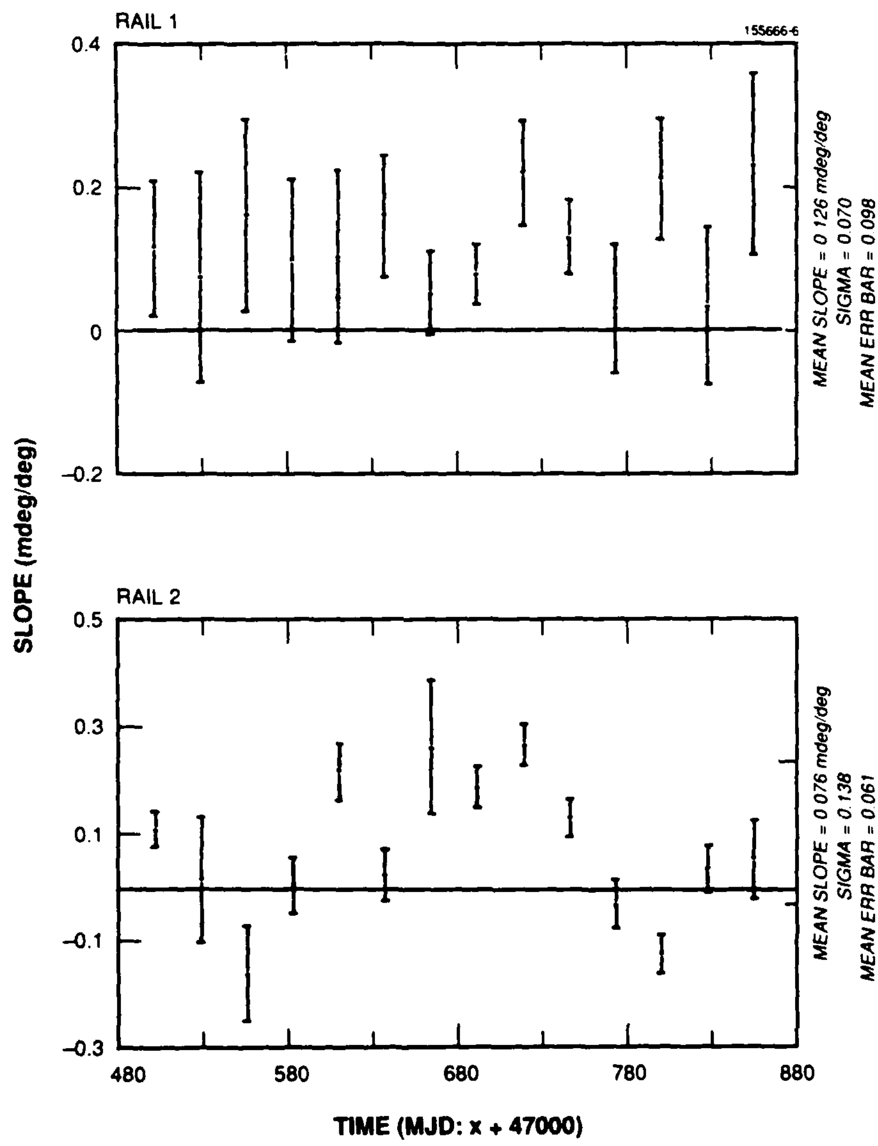
date	bias(mdeg)	b(mdeg/deg)	c(mdeg/(deg*deg))
46047	293.0	-0.347	0.0
46229	293.0	-0.340	0.0
46241	293.0	-0.340	0.0
46334	293.0	-0.340	0.0
46389	293.0	-0.340	0.0
46534	305.0	-0.340	0.0
46954	293.7	-0.340	0.0
47008	43.0	-0.340	0.0
47034	28.0	-0.340	0.0
47231	34.0	-0.340	0.0
47412	40.0	-0.340	0.0
47447	40.0	-0.340	0.0
47455	40.0	-0.340	0.0
47536	28.0	+0.292	-6.277E-3
47663	32.0	+0.292	-6.277E-3
47852	32.0	+0.292	-6.277E-3
47873	32.0	+0.292	-6.277E-3

APPENDIX B
LAGEOS AZIMUTH MODEL PARAMETERS VERSUS TIME

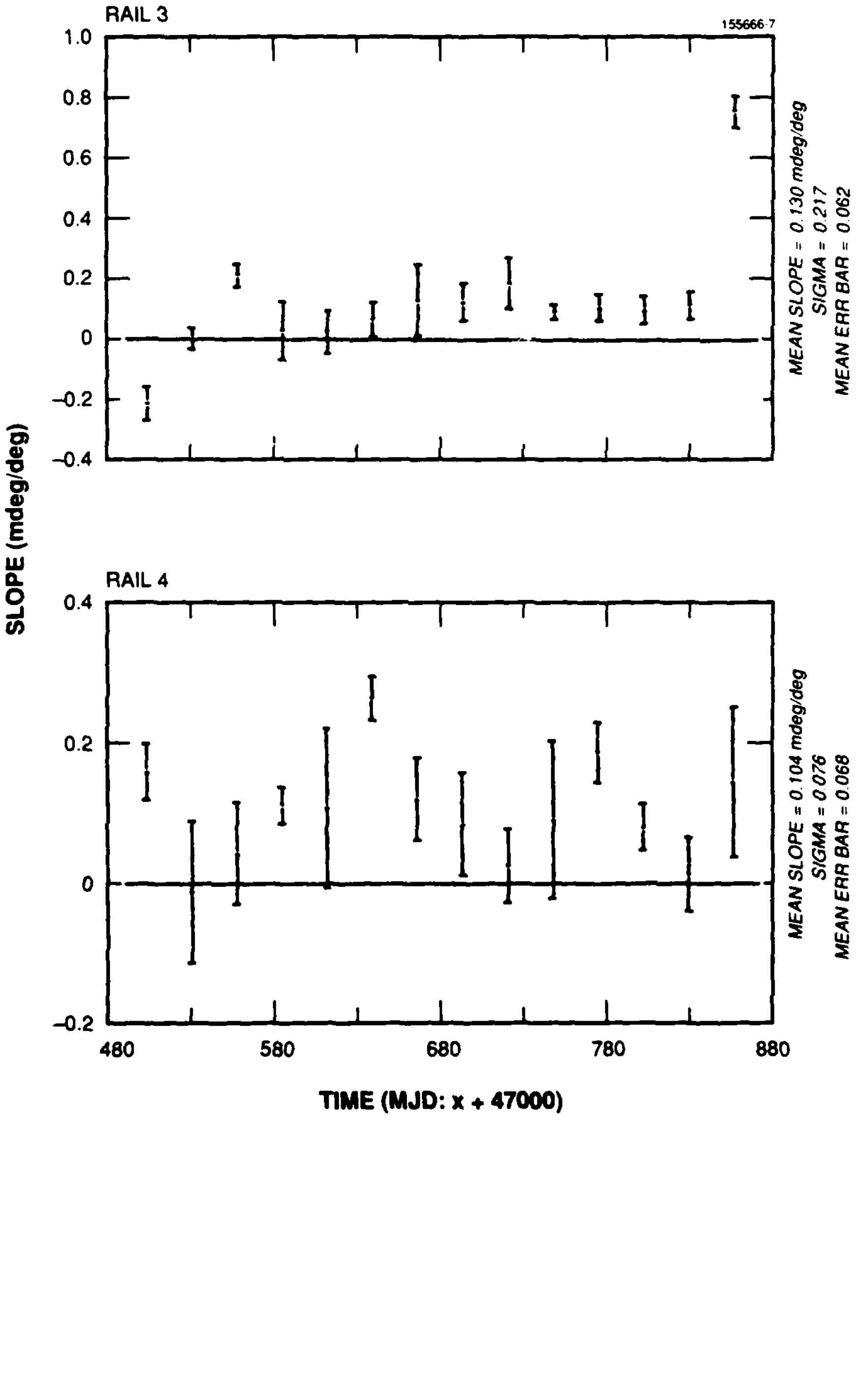
LAGEOS, DECEMBER 1988 — DECEMBER 1989



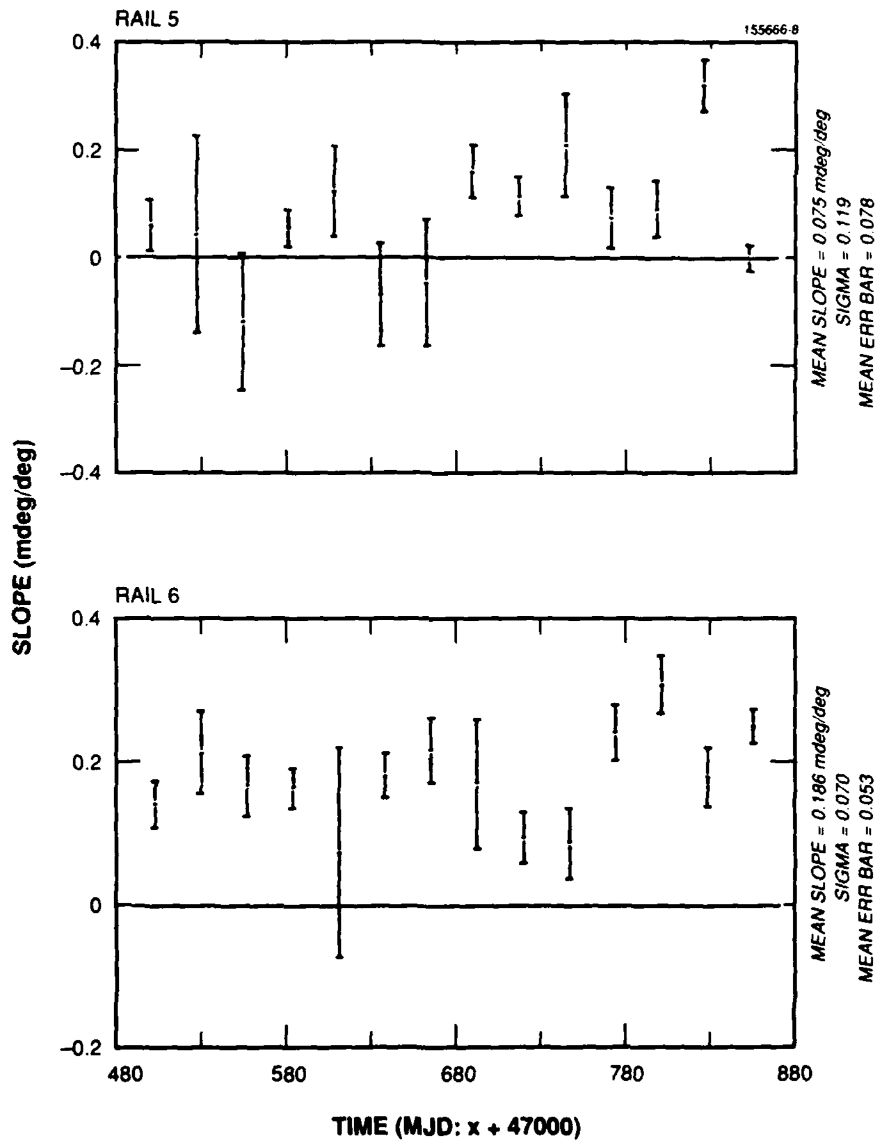
SLOPE VERSUS TIME: LAGEOS, DECEMBER 1988 — DECEMBER 1989



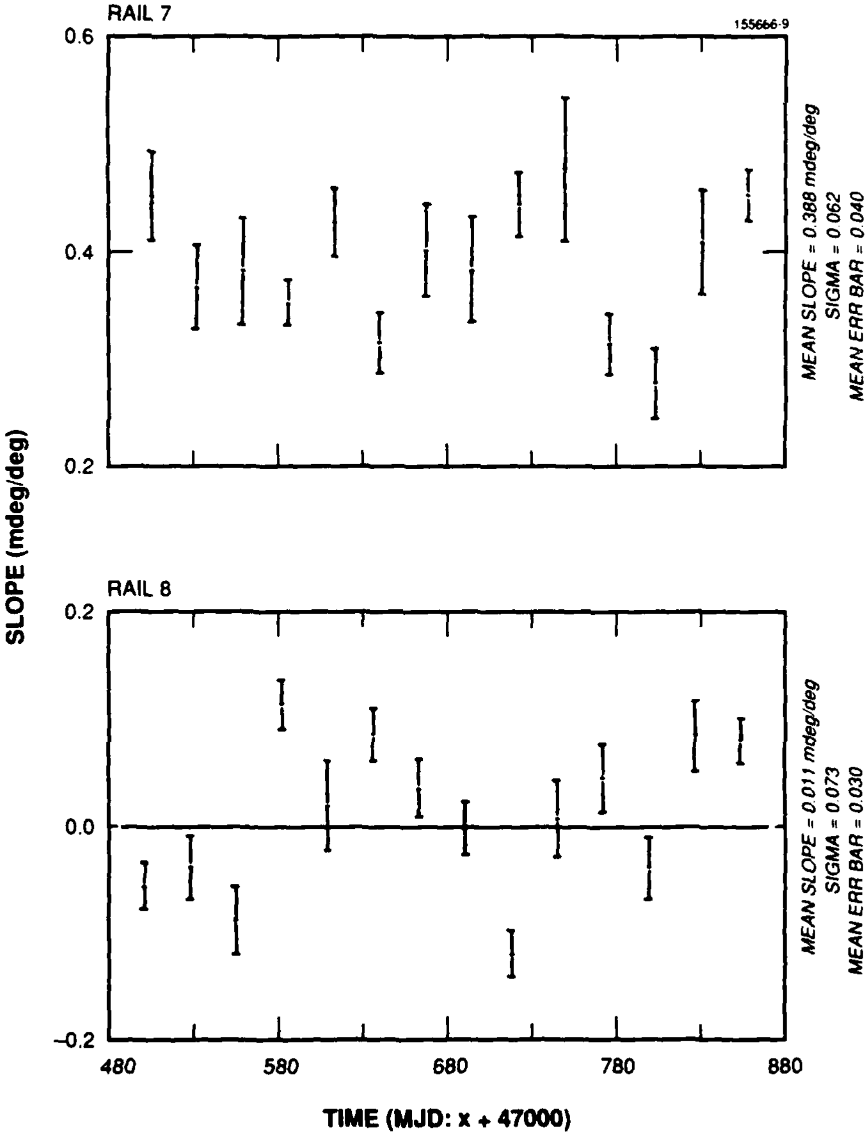
SLOPE VERSUS TIME: LAGEOS, DECEMBER 1988 — DECEMBER 1989



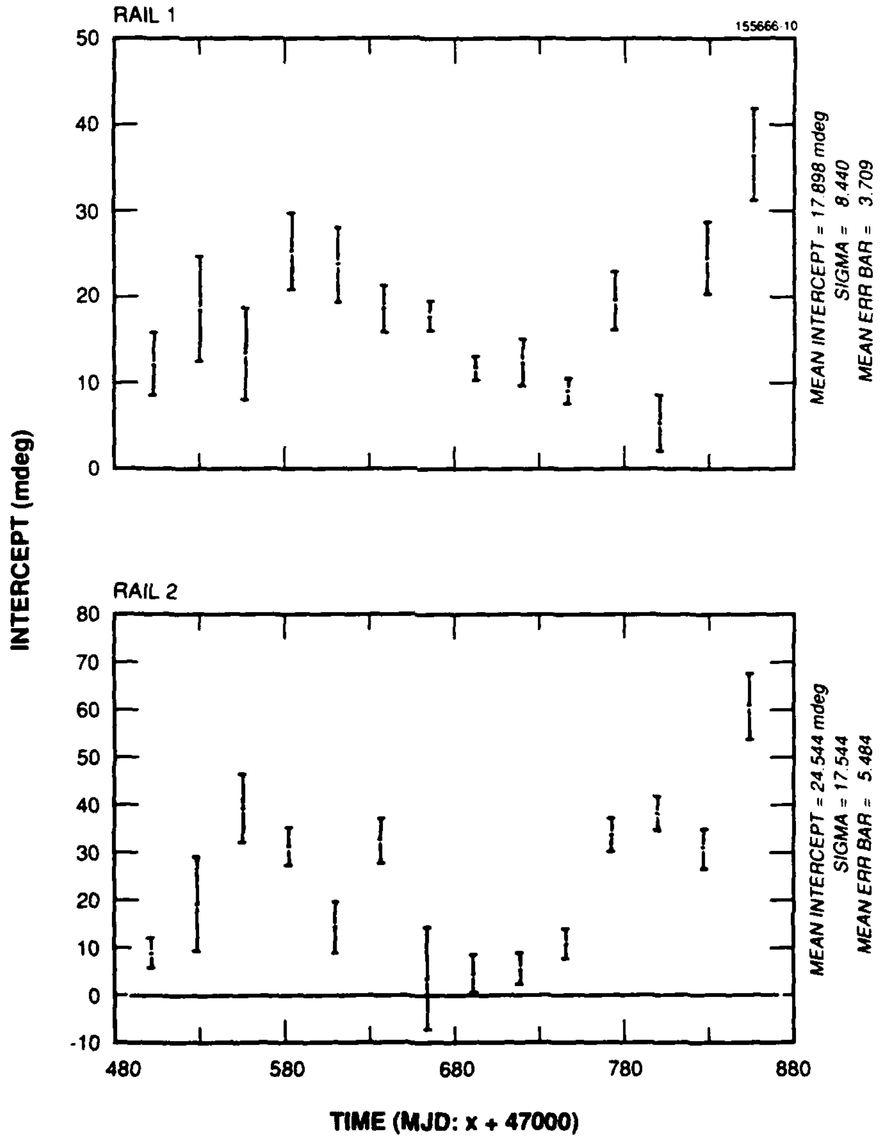
SLOPE VERSUS TIME: LAGEOS, DECEMBER 1988 — DECEMBER 1989



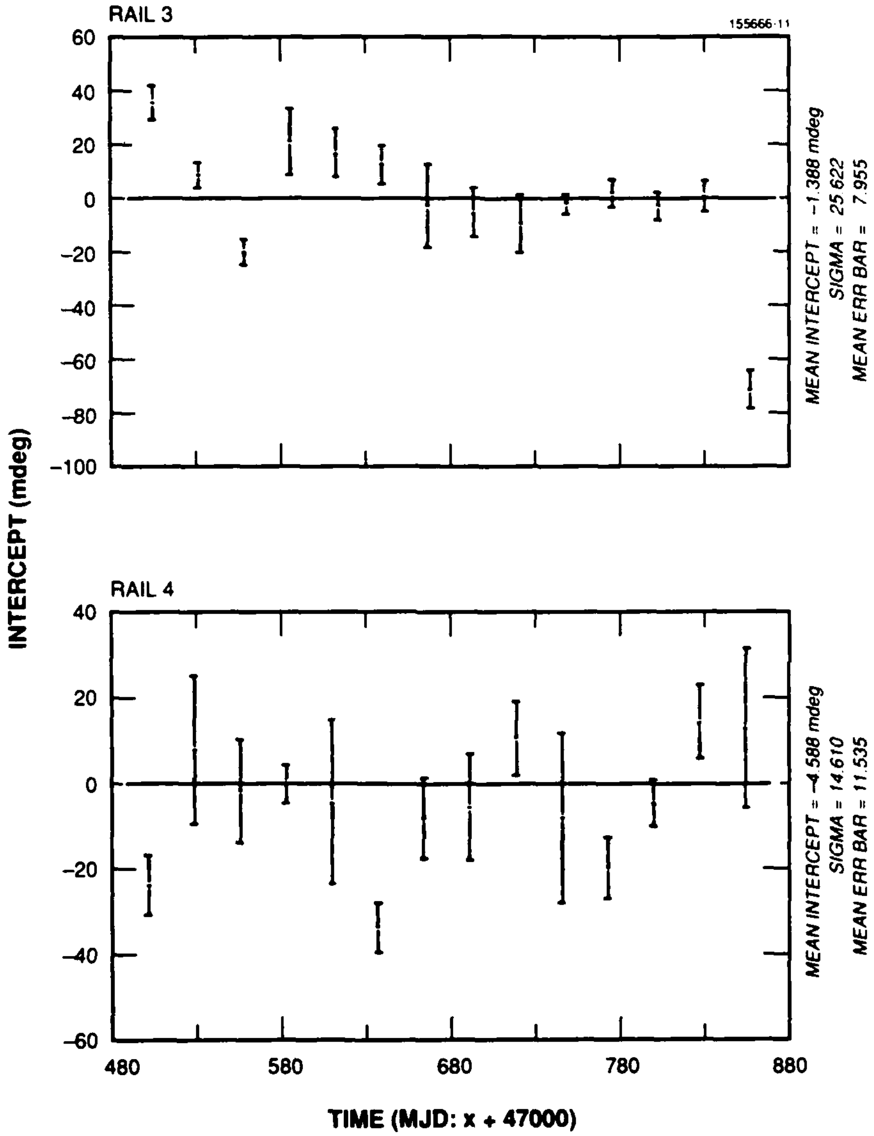
SLOPE VERSUS TIME: LAGEOS, DECEMBER 1988 — DECEMBER 1989



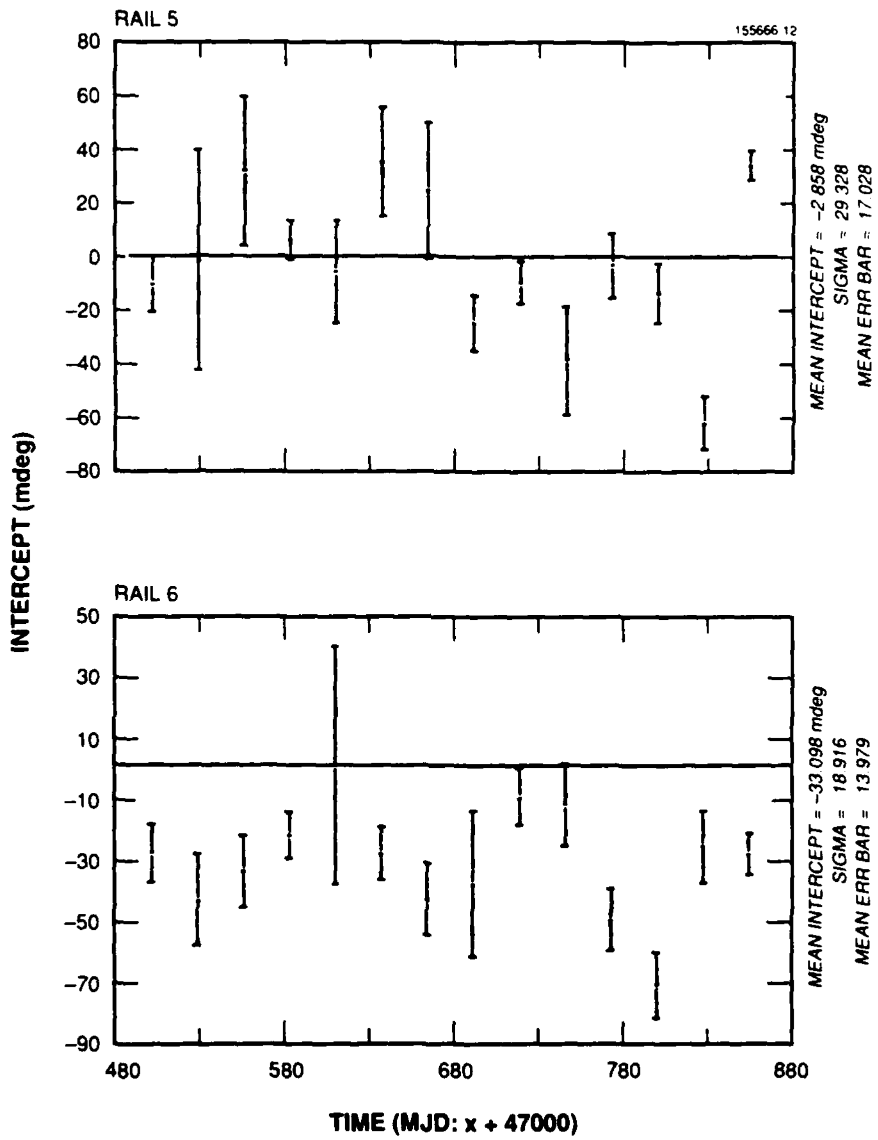
INTERCEPT VERSUS TIME: LAGEOS, DECEMBER 1988 — DECEMBER 1989



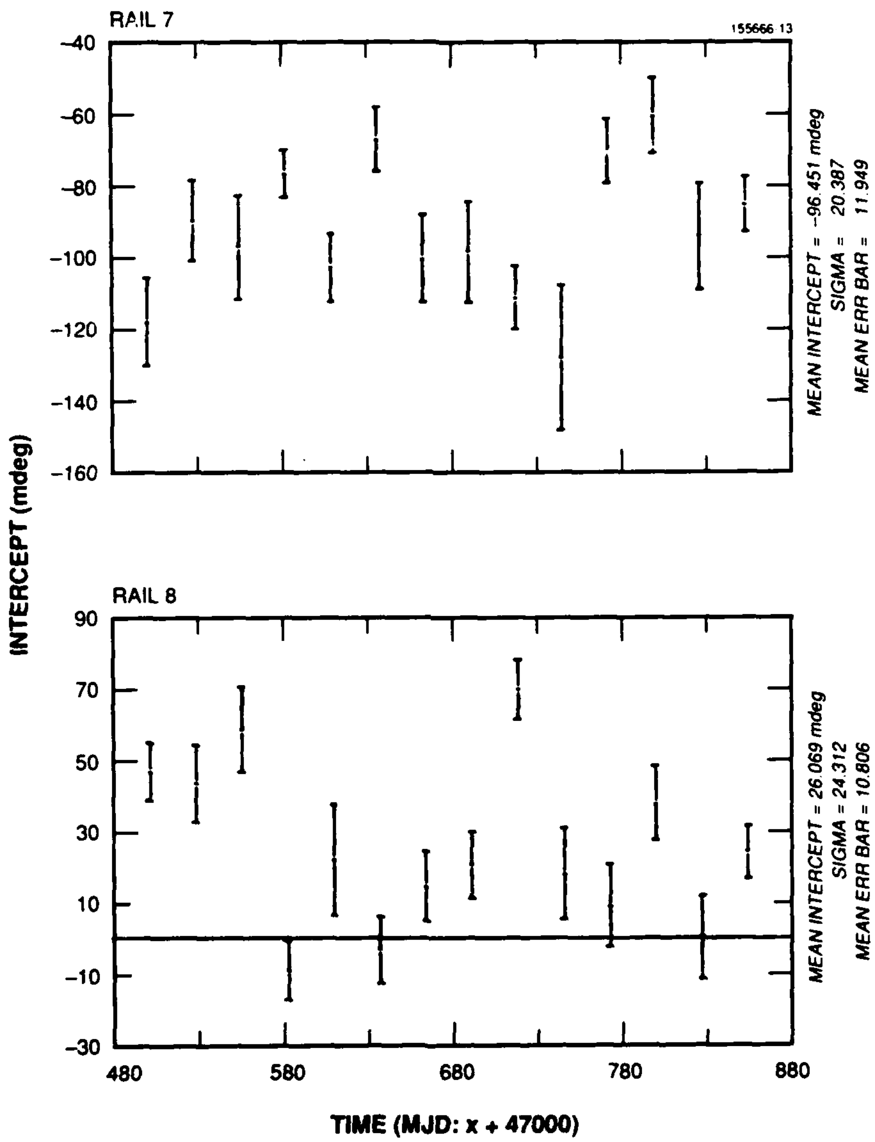
INTERCEPT VERSUS TIME: LAGEOS, DECEMBER 1988 — DECEMBER 1989



INTERCEPT VERSUS TIME: LAGEOS, DECEMBER 1988 — DECEMBER 1989

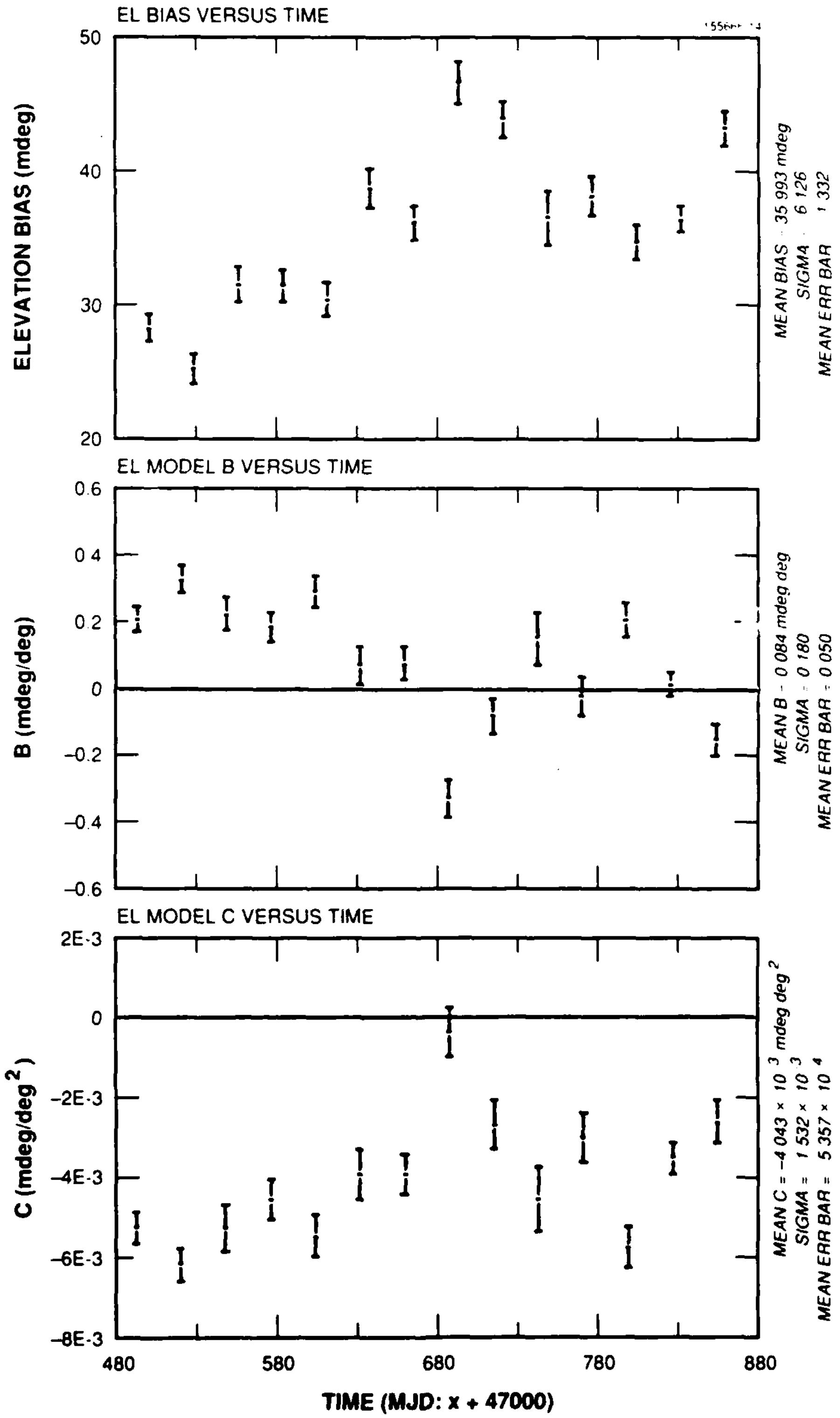


INTERCEPT VERSUS TIME: LAGEOS, DECEMBER 1988 — DECEMBER 1989



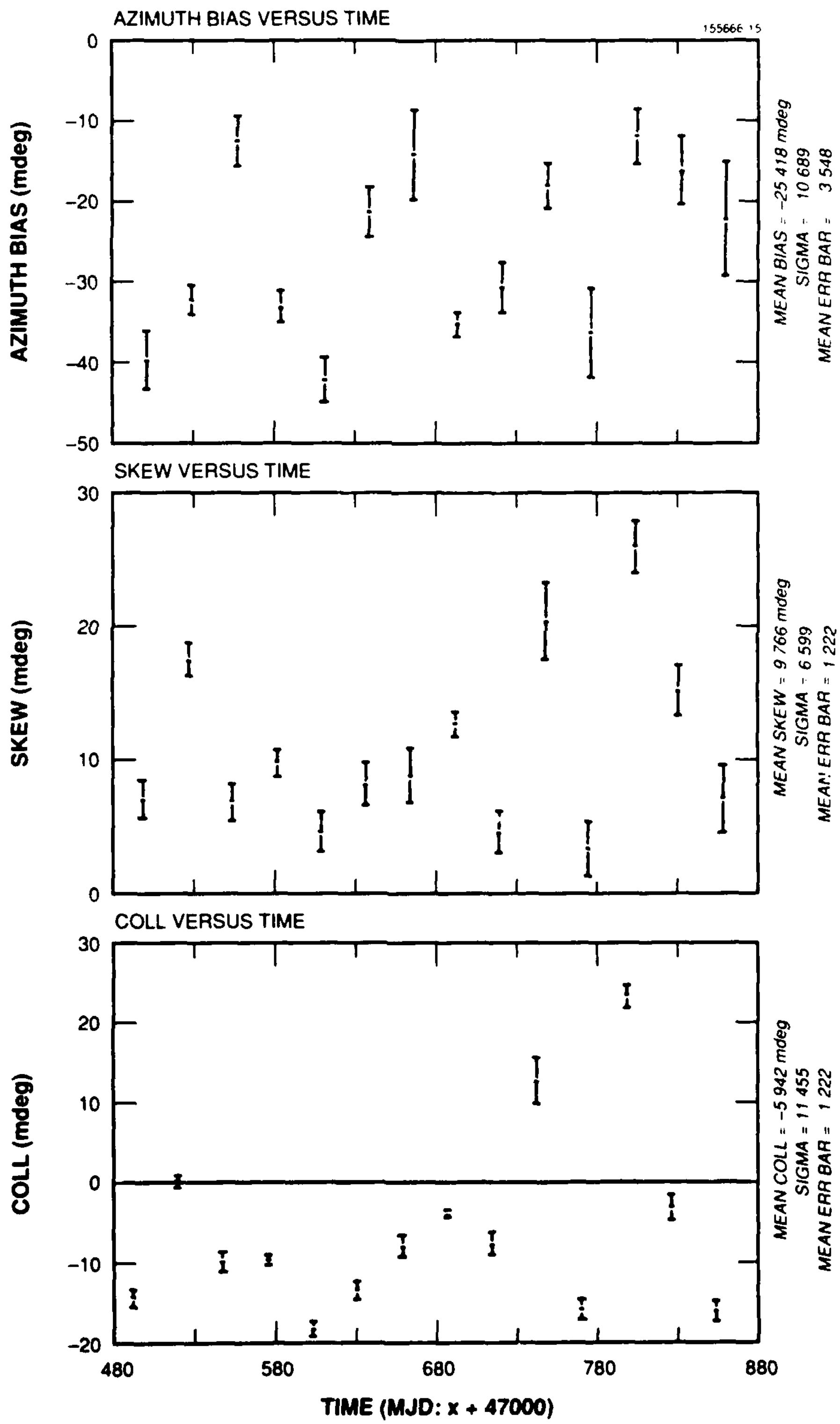
APPENDIX C
LAGEOS ELEVATION MODEL PARAMETERS VERSUS TIME

LAGEOS: ALL DATA, DECEMBER 1988 — DECEMBER 1989

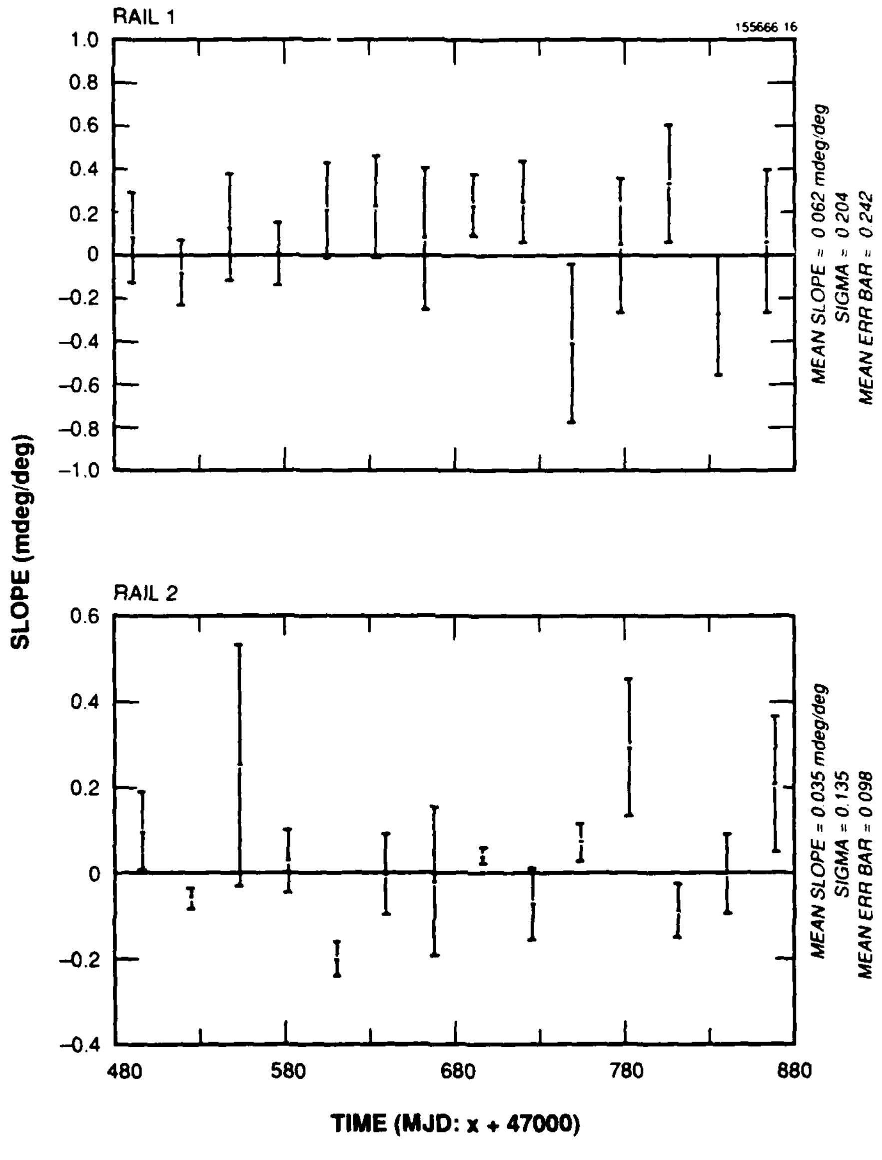


APPENDIX D
EGP AZIMUTH MODEL PARAMETERS VERSUS TIME

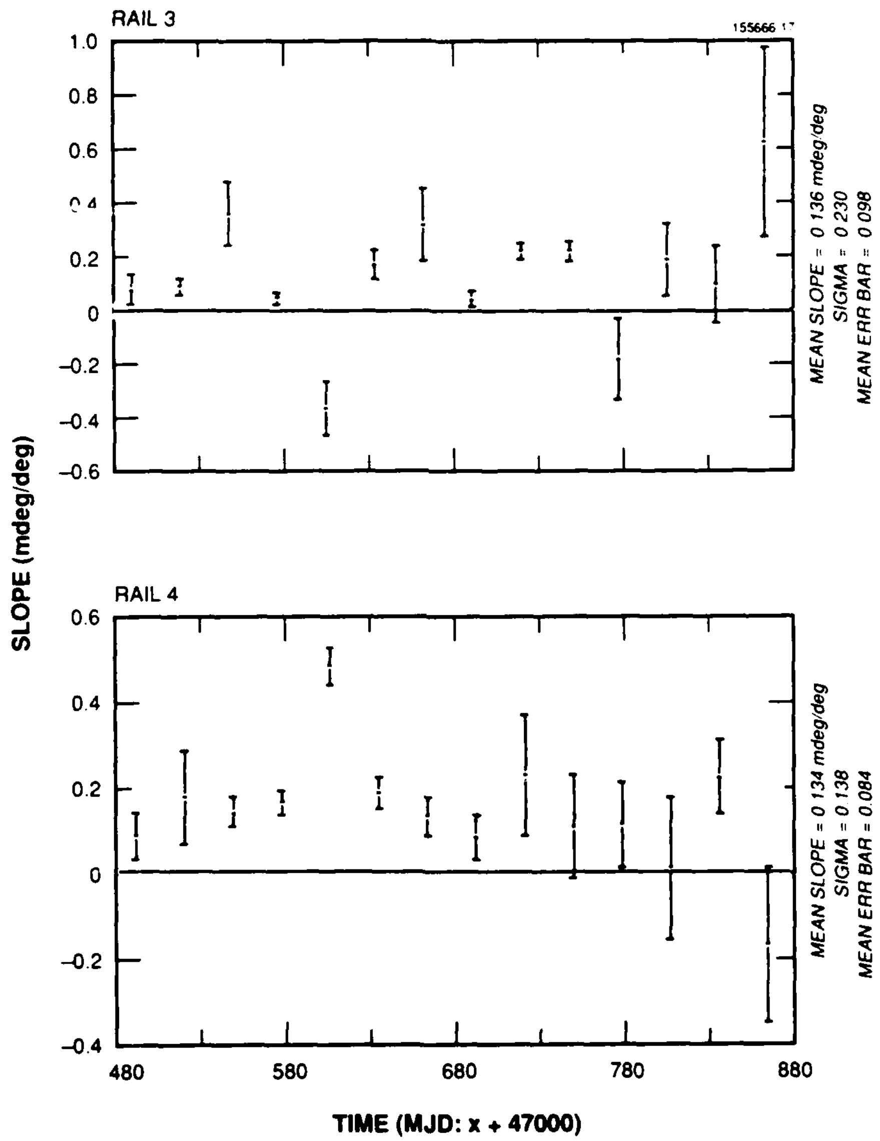
EGP, DECEMBER 1988 — DECEMBER 1989



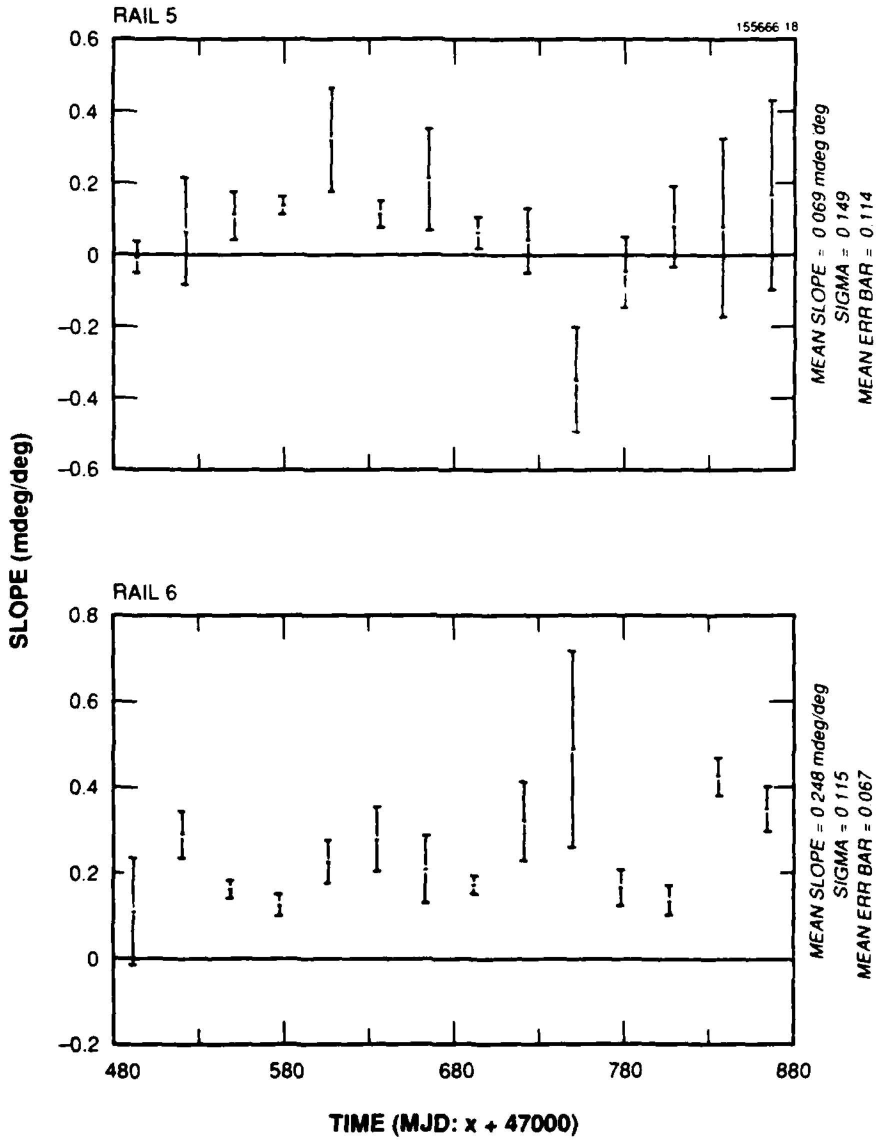
SLOPE VERSUS TIME: EGP, DECEMBER 1988 — DECEMBER 1989



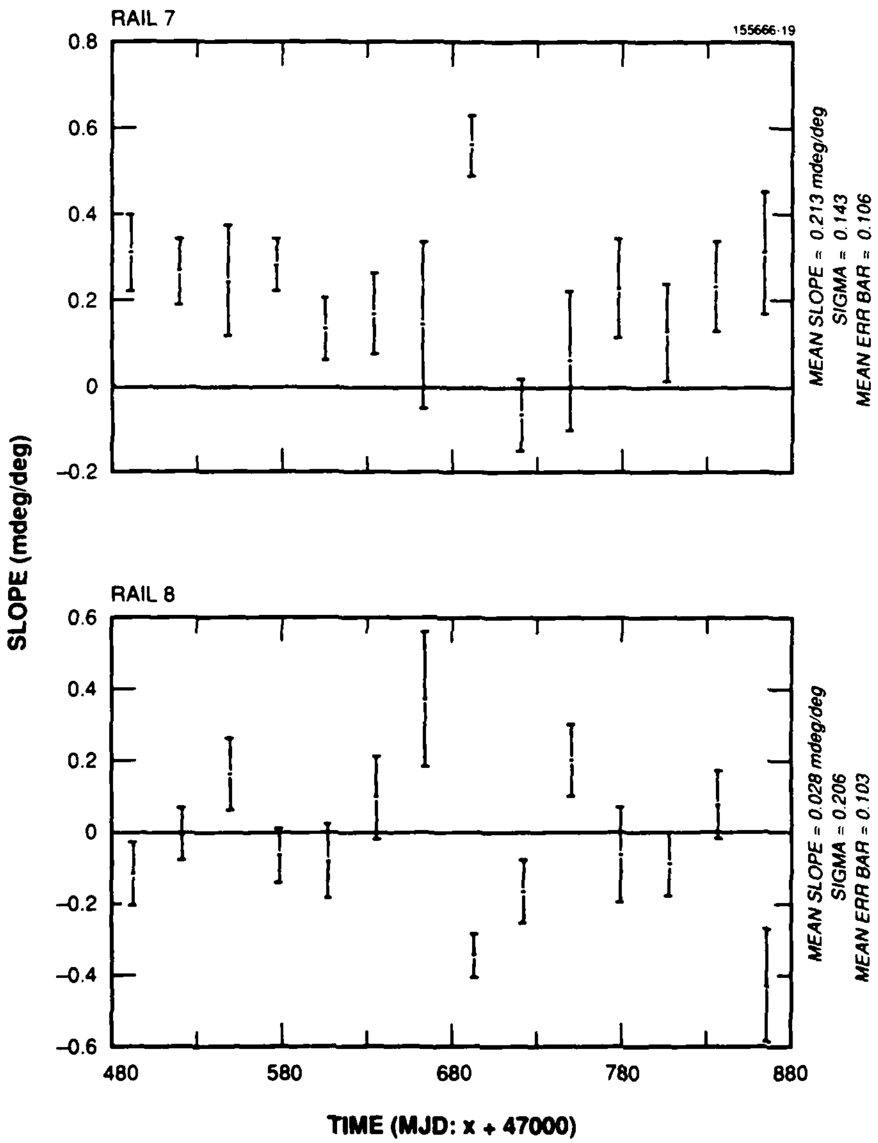
SLOPE VERSUS TIME: EGP, DECEMBER 1988 — DECEMBER 1989



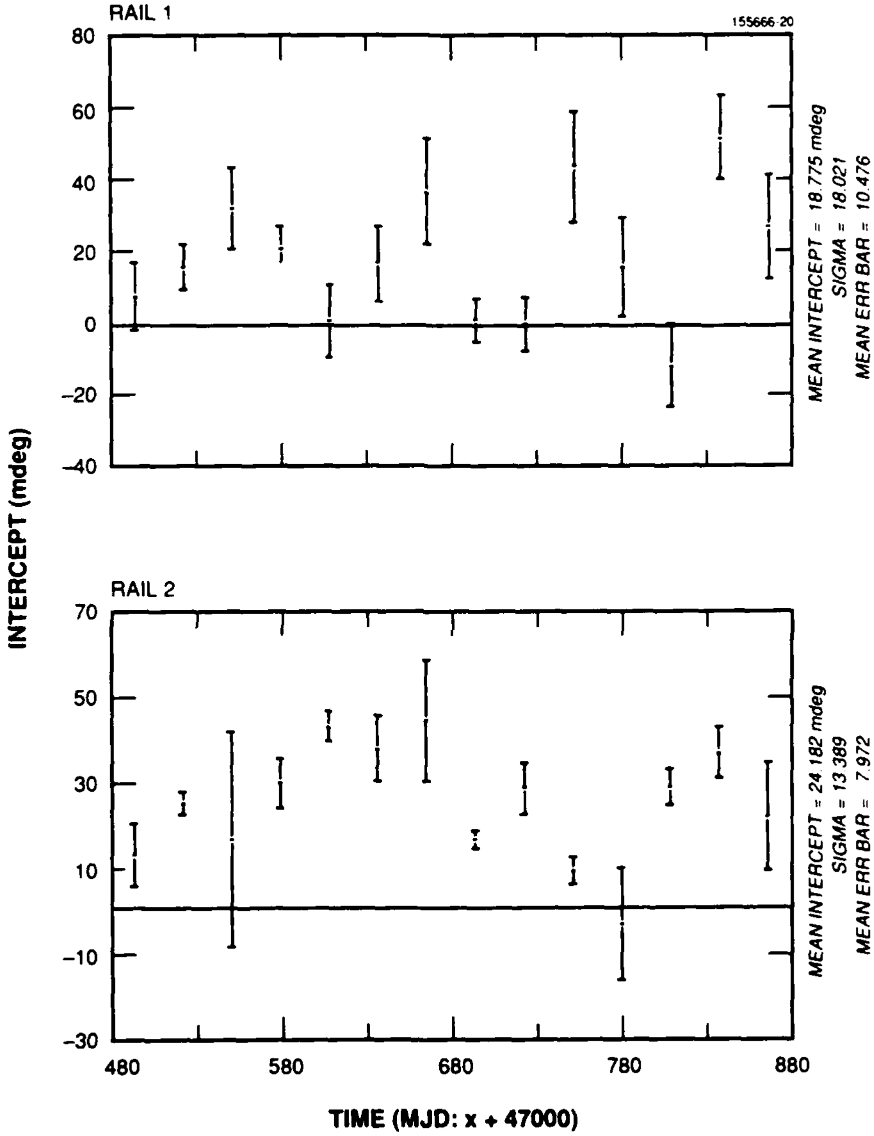
SLOPE VERSUS TIME: EGP, DECEMBER 1988 — DECEMBER 1989



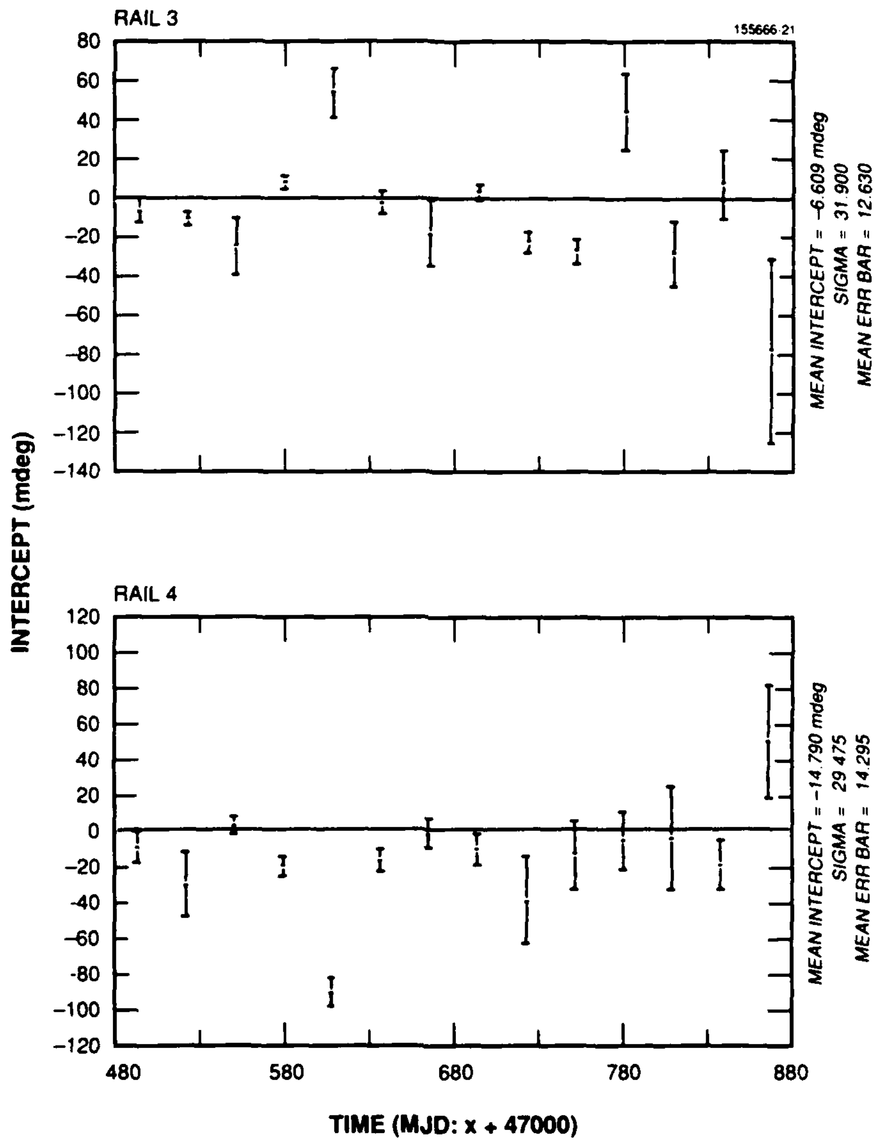
SLOPE VERSUS TIME: EGP, DECEMBER 1988 — DECEMBER 1989



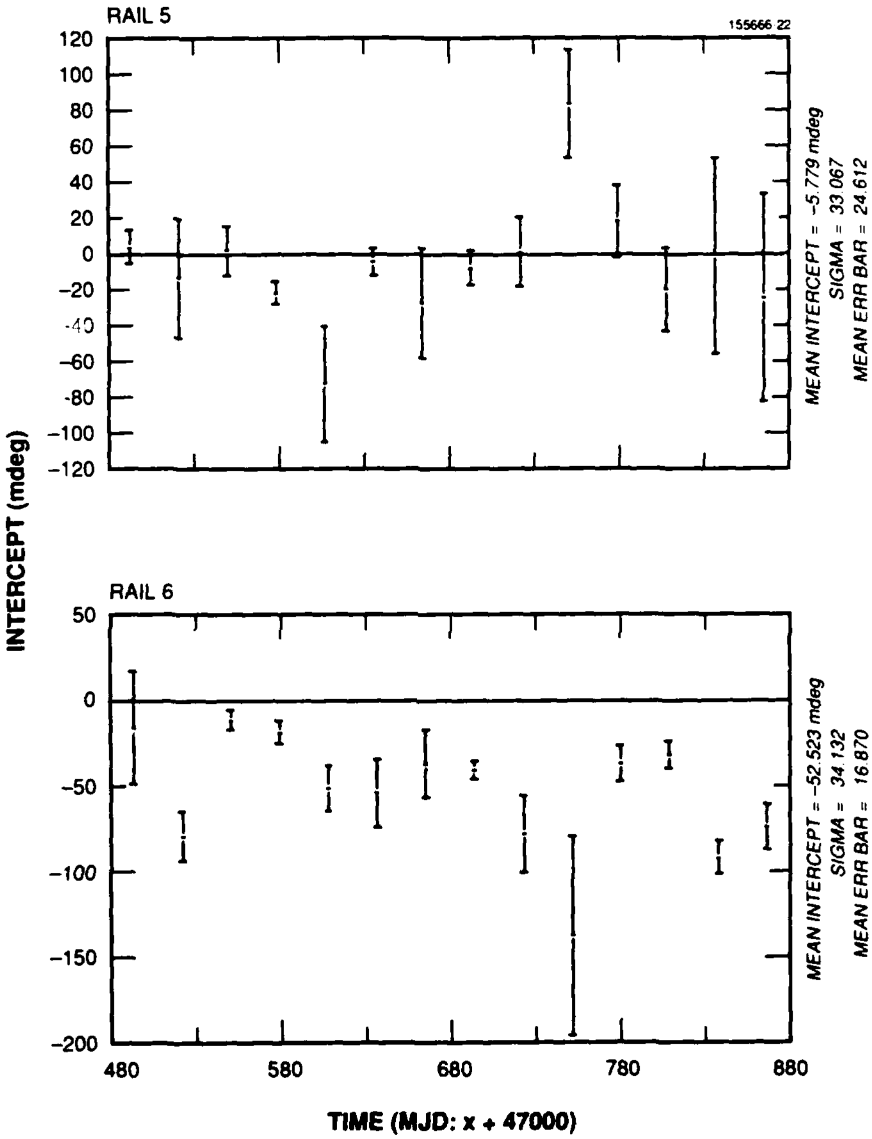
INTERCEPT VERSUS TIME: EGP, DECEMBER 1988 — DECEMBER 1989



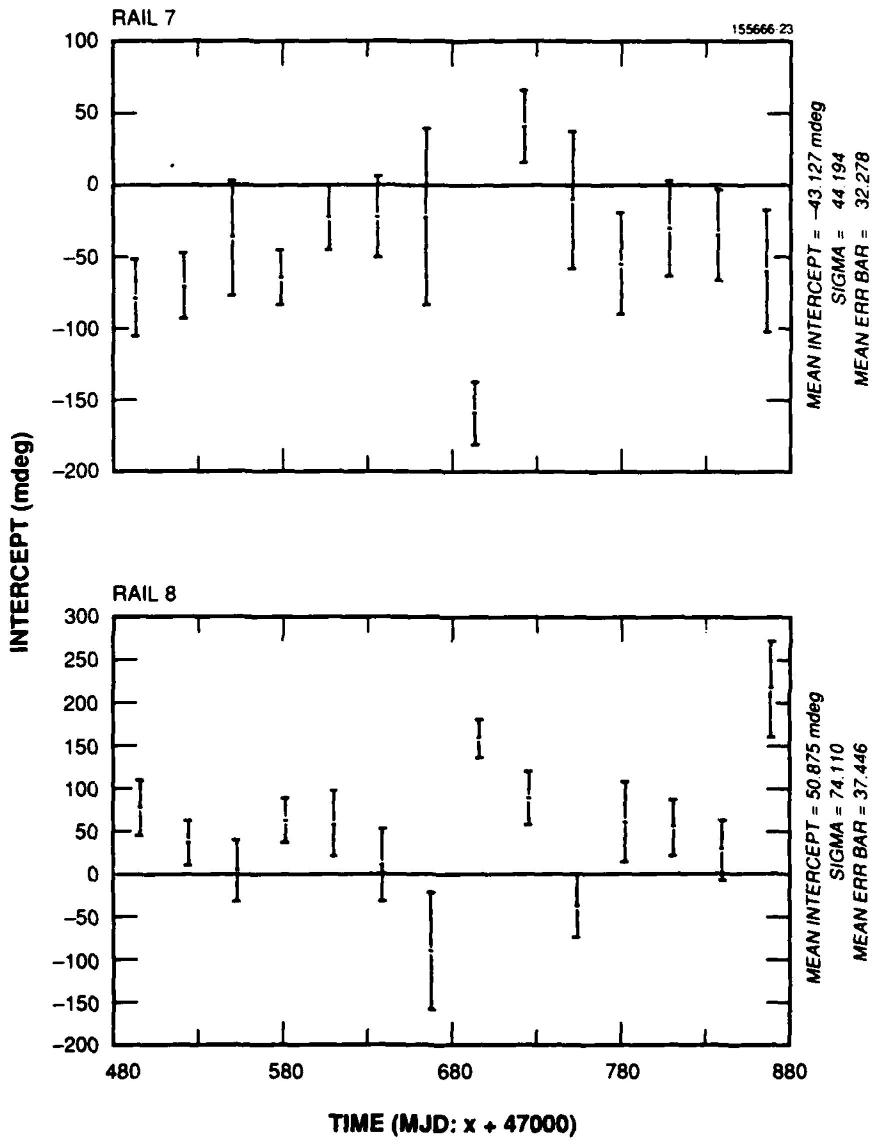
INTERCEPT VERSUS TIME: EGP, DECEMBER 1988 — DECEMBER 1989



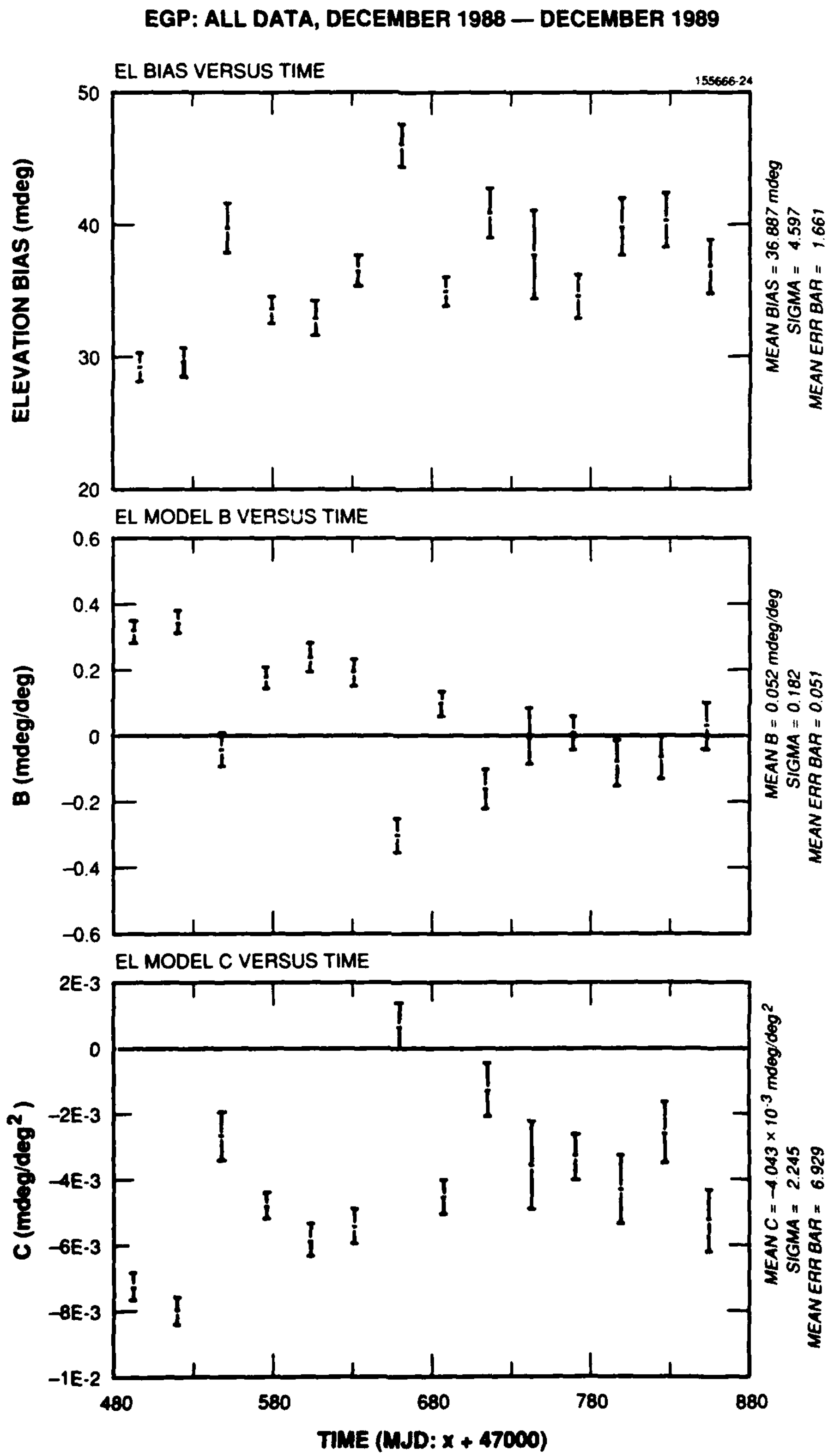
INTERCEPT VERSUS TIME: EGP, DECEMBER 1988 — DECEMBER 1989



INTERCEPT VERSUS TIME: EGP, DECEMBER 1988 — DECEMBER 1989

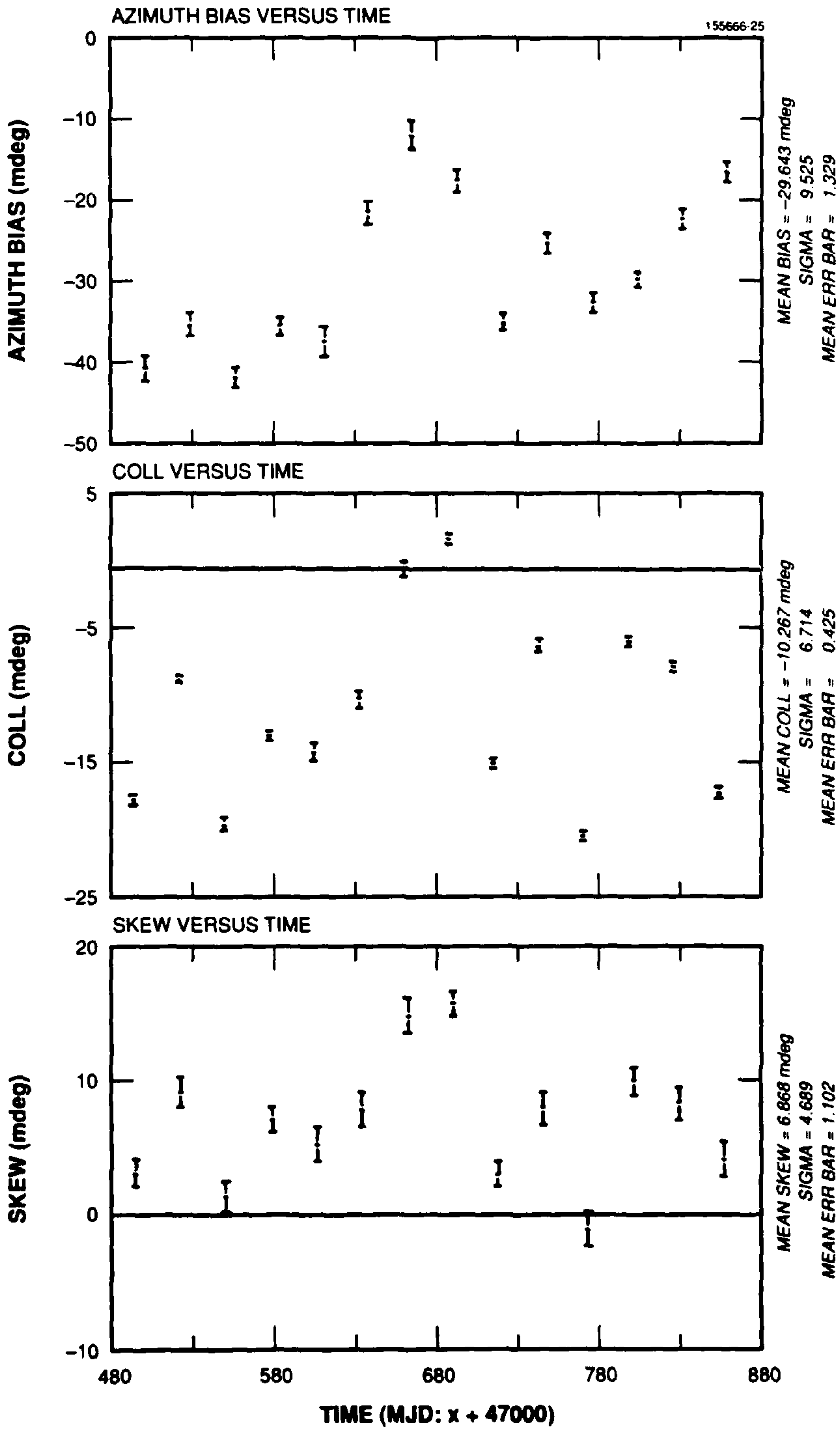


APPENDIX E
EGP ELEVATION MODEL PARAMETERS VERSUS TIME

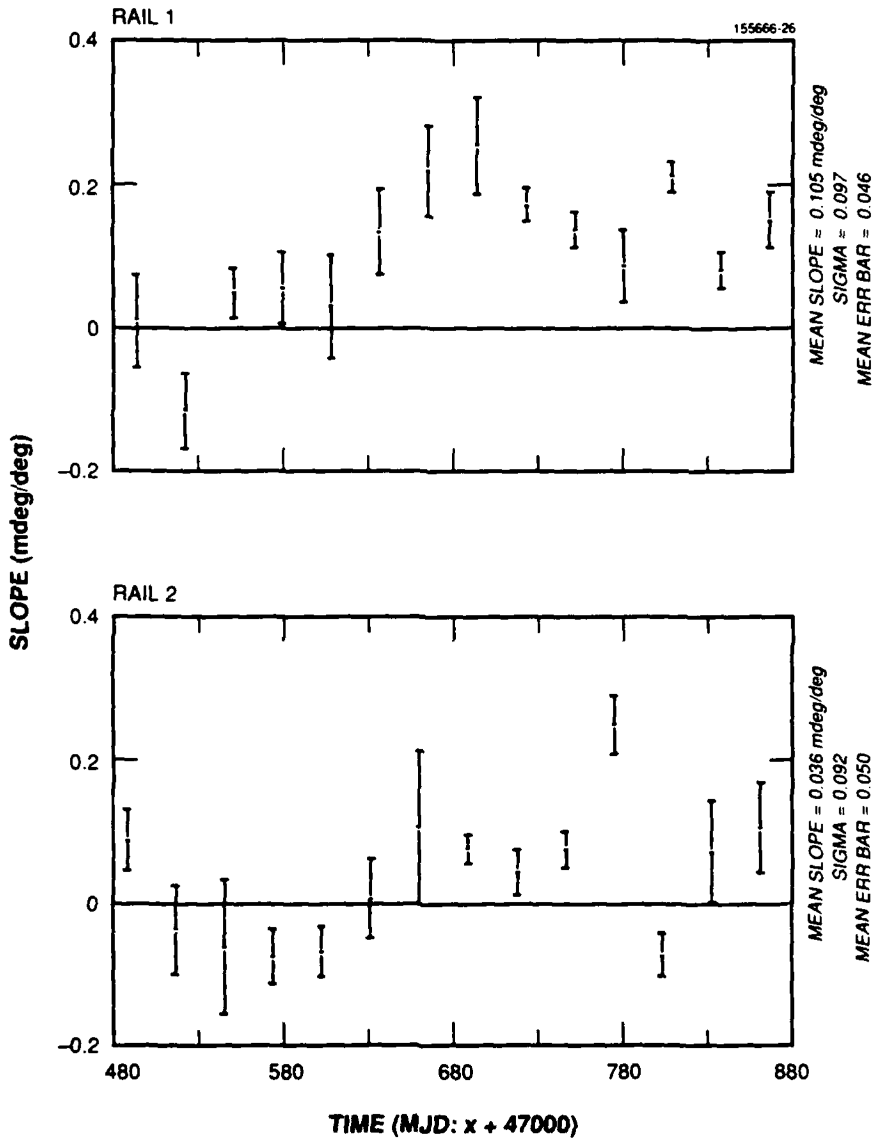


APPENDIX F
JOINT AZIMUTH MODEL PARAMETERS VERSUS TIME

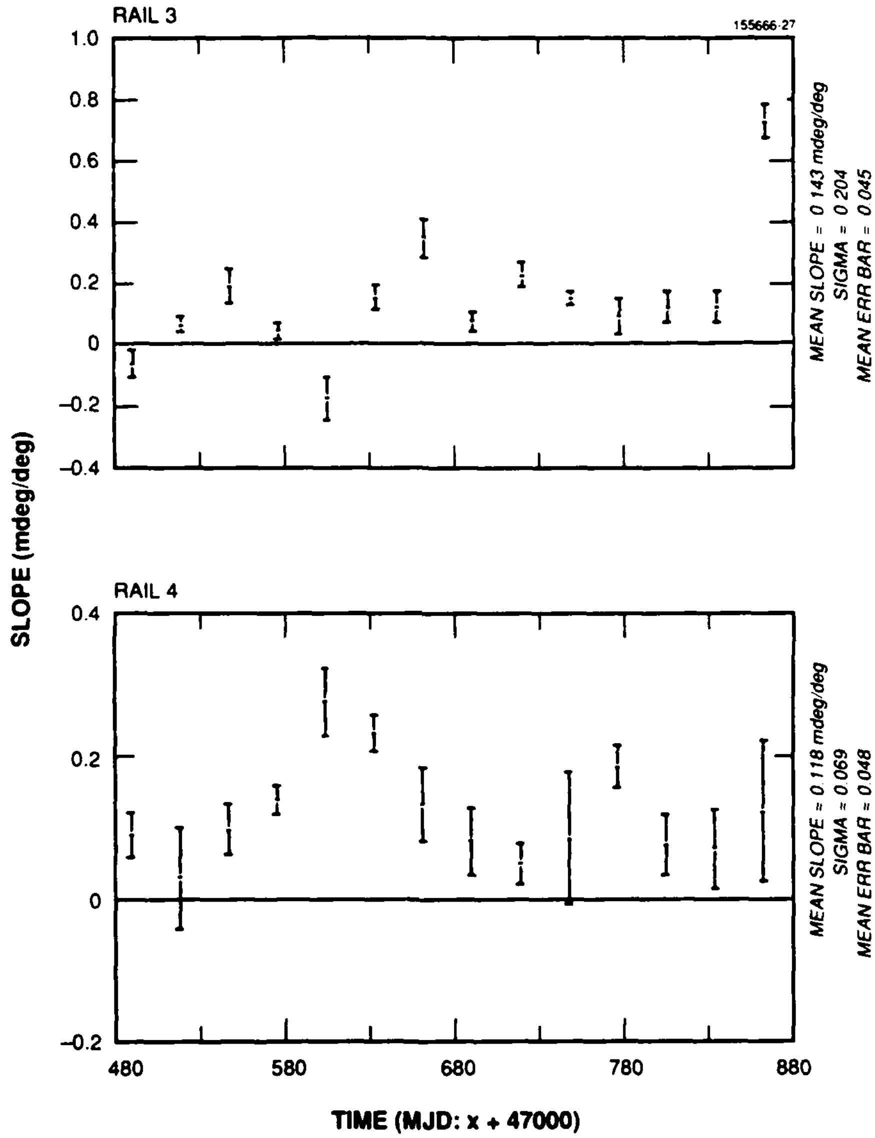
LAGEOS + EGP, DECEMBER 1988 — DECEMBER 1989



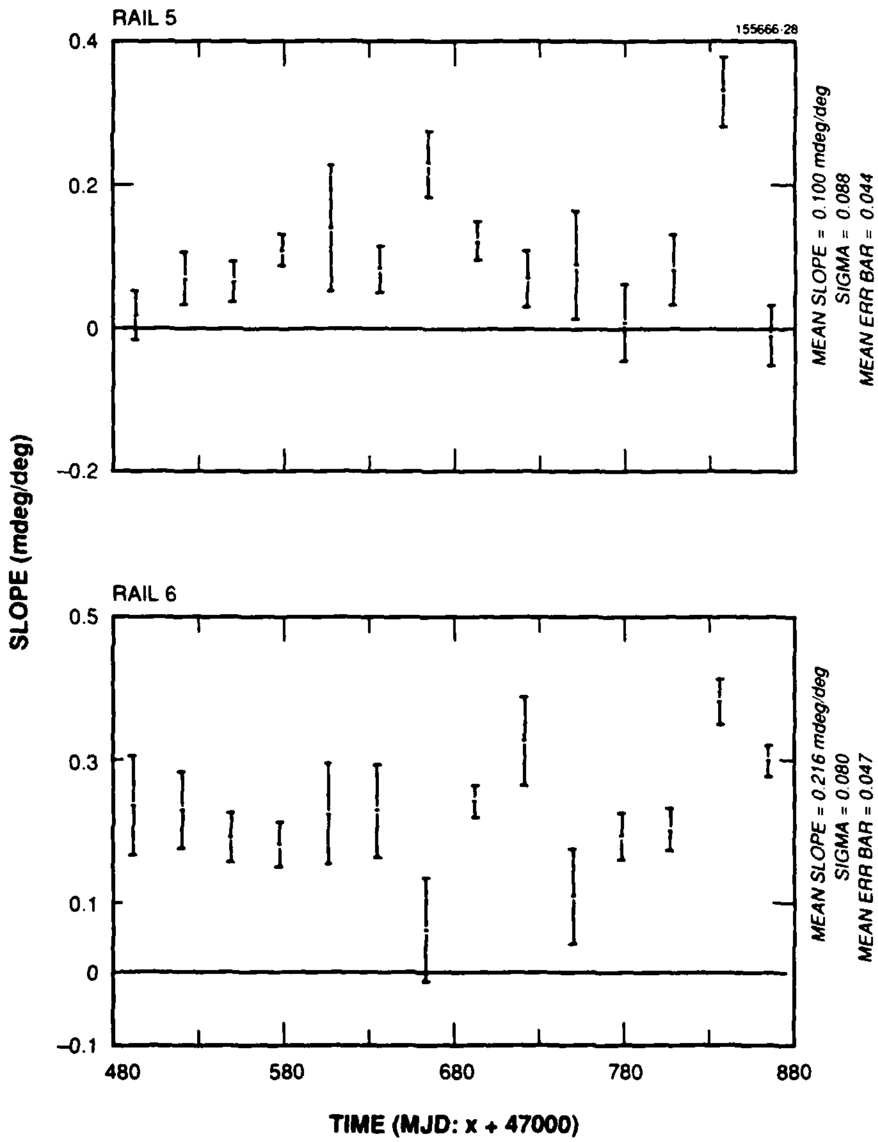
SLOPE VERSUS TIME: LAGEOS + EGP, DECEMBER 1988 — DECEMBER 1989



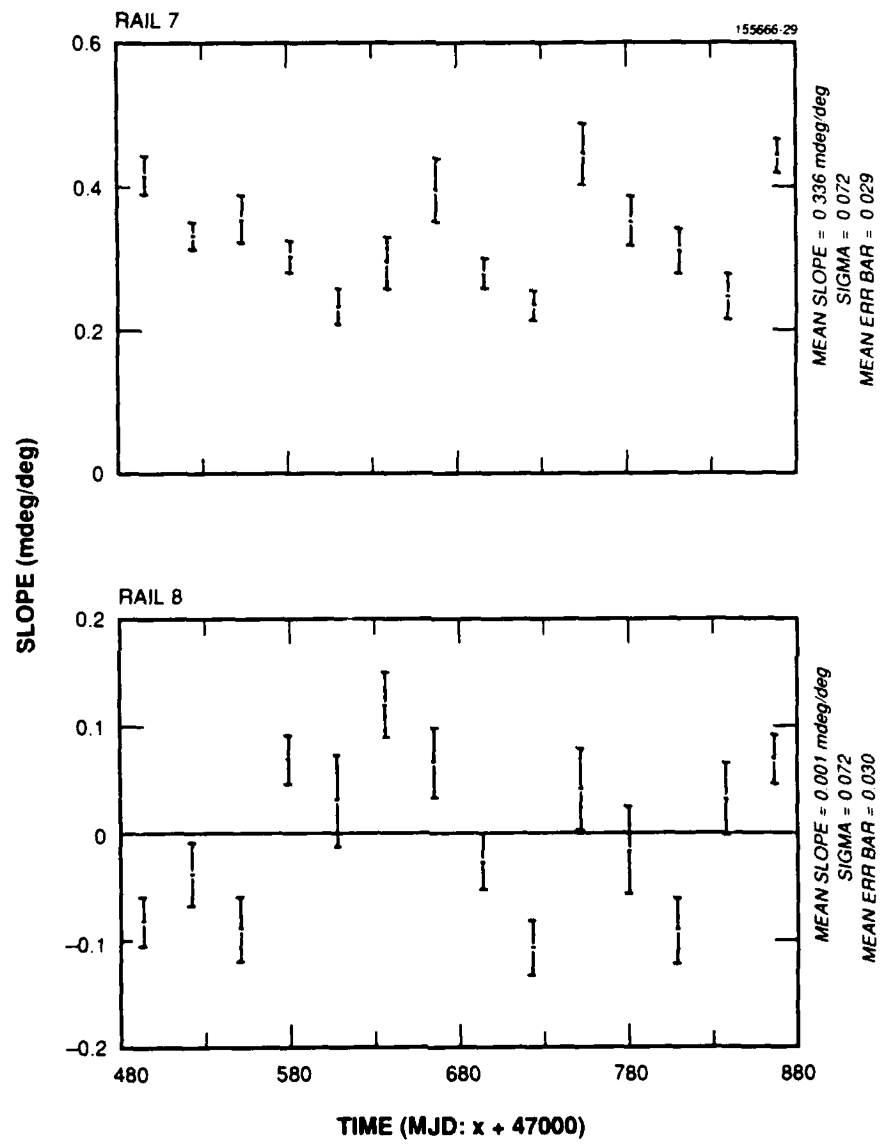
SLOPE VERSUS TIME: LAGEOS + EGP, DECEMBER 1988 — DECEMBER 1989



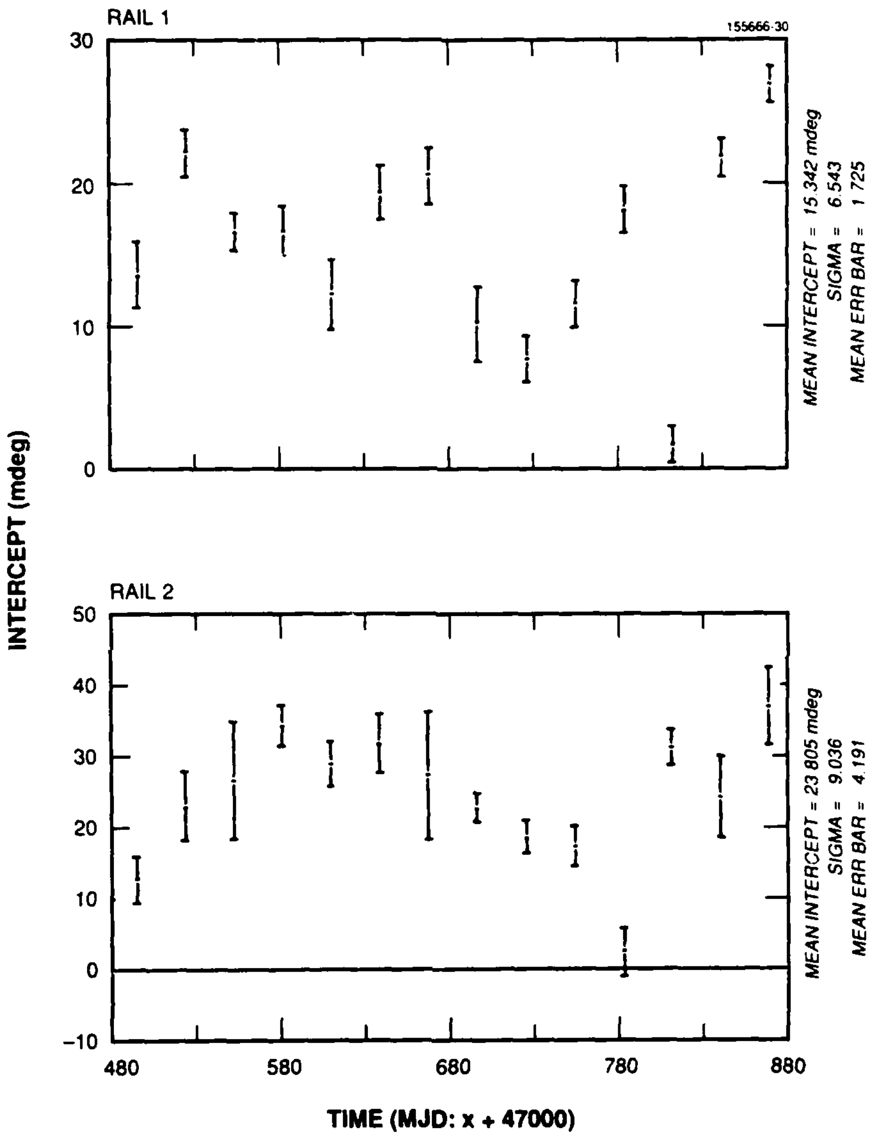
SLOPE VERSUS TIME: LAGEOS + EGP, DECEMBER 1988 — DECEMBER 1989



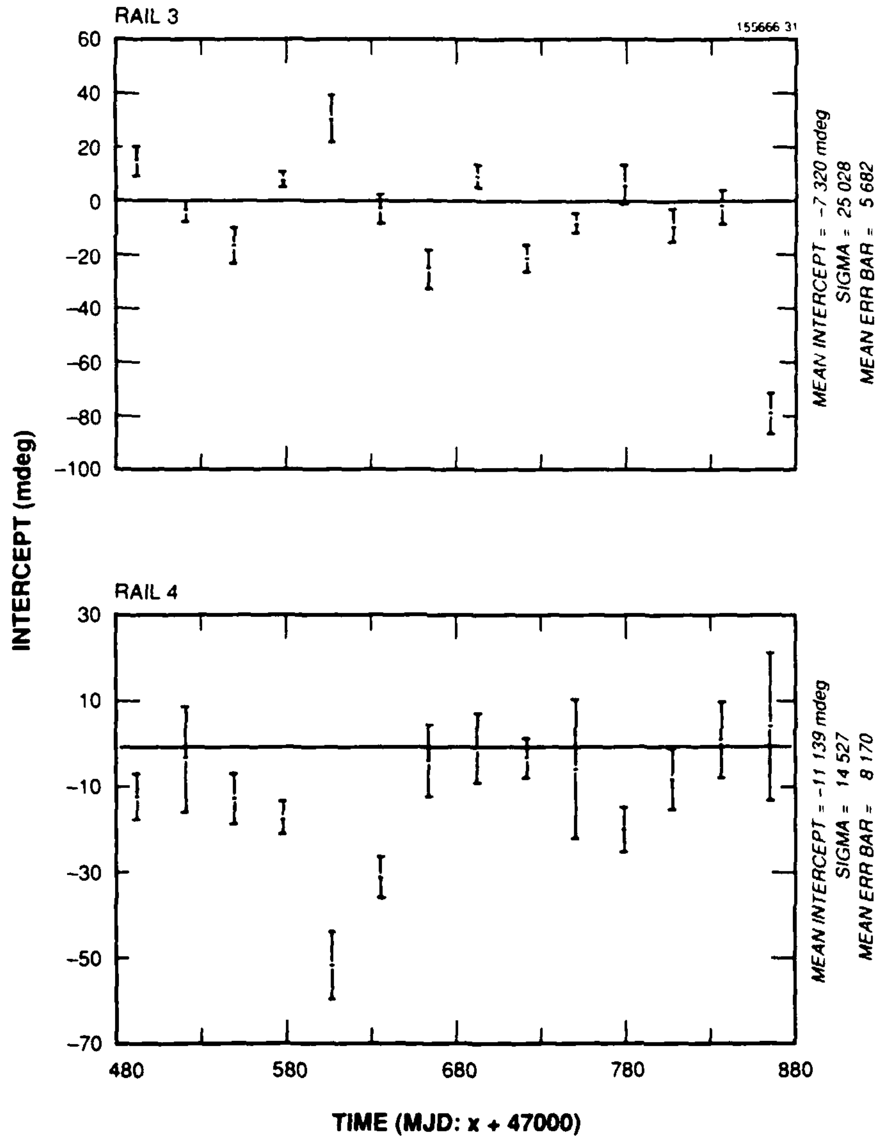
SLOPE VERSUS TIME: LAGEOS + EGP, DECEMBER 1988 — DECEMBER 1989



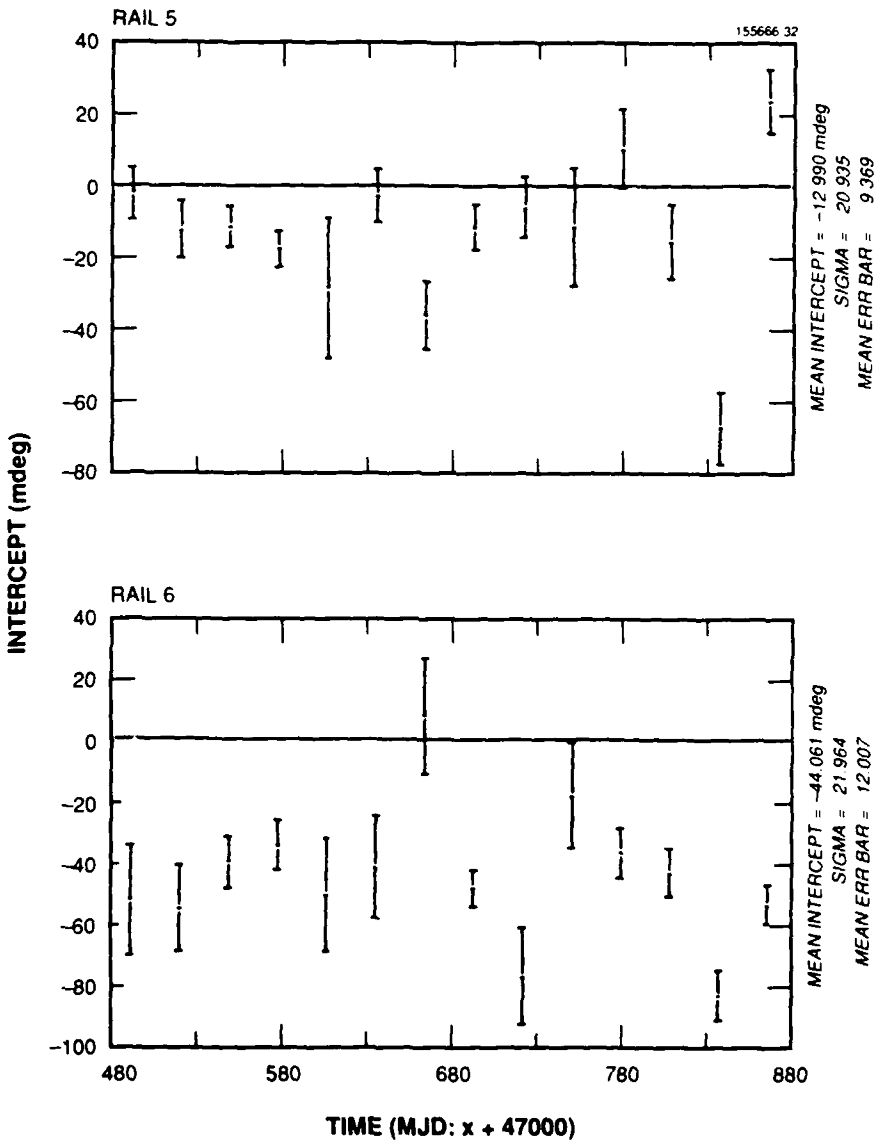
INTERCEPT VERSUS TIME: LAGEOS + EGP, DECEMBER 1988 — DECEMBER 1989



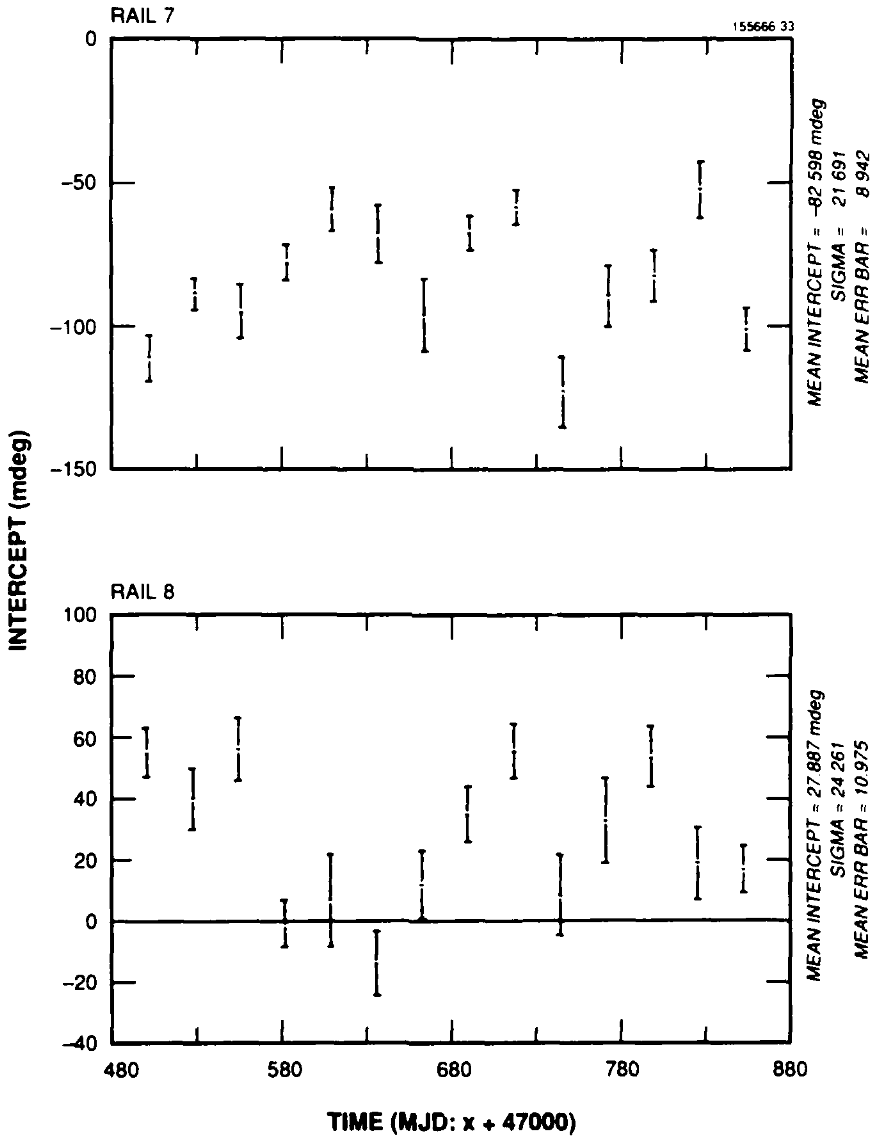
INTERCEPT VERSUS TIME: LAGEOS + EGP, DECEMBER 1988 — DECEMBER 1989



INTERCEPT VERSUS TIME: LAGEOS + EGP, DECEMBER 1988 — DECEMBER 1989



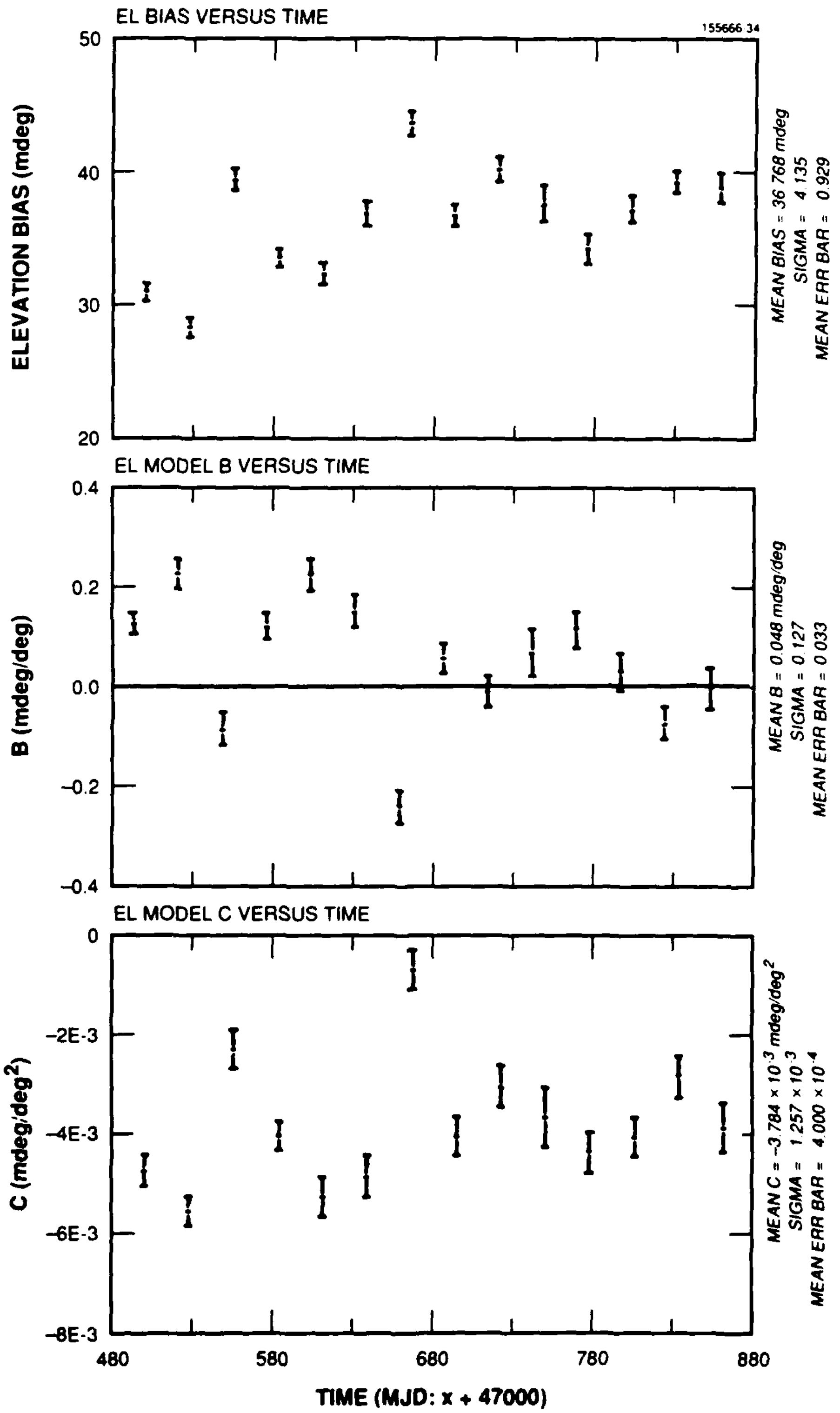
INTERCEPT VERSUS TIME: LAGEOS + EGP, DECEMBER 1988 — DECEMBER 1989



APPENDIX G

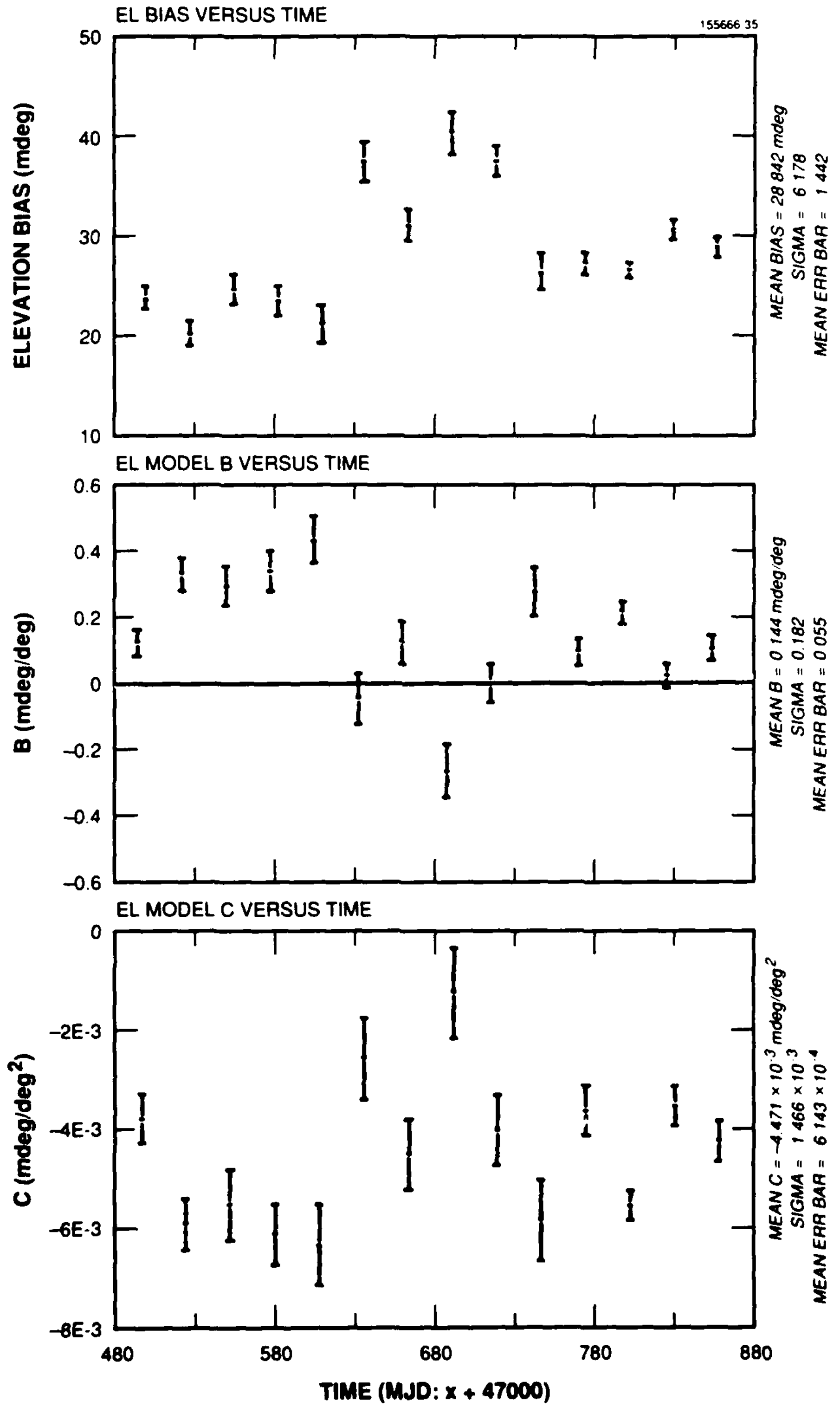
JOINT ELEVATION MODEL PARAMETERS VERSUS TIME

LAGEOS + EGP: ALL DATA, DECEMBER 1988 — DECEMBER 1989



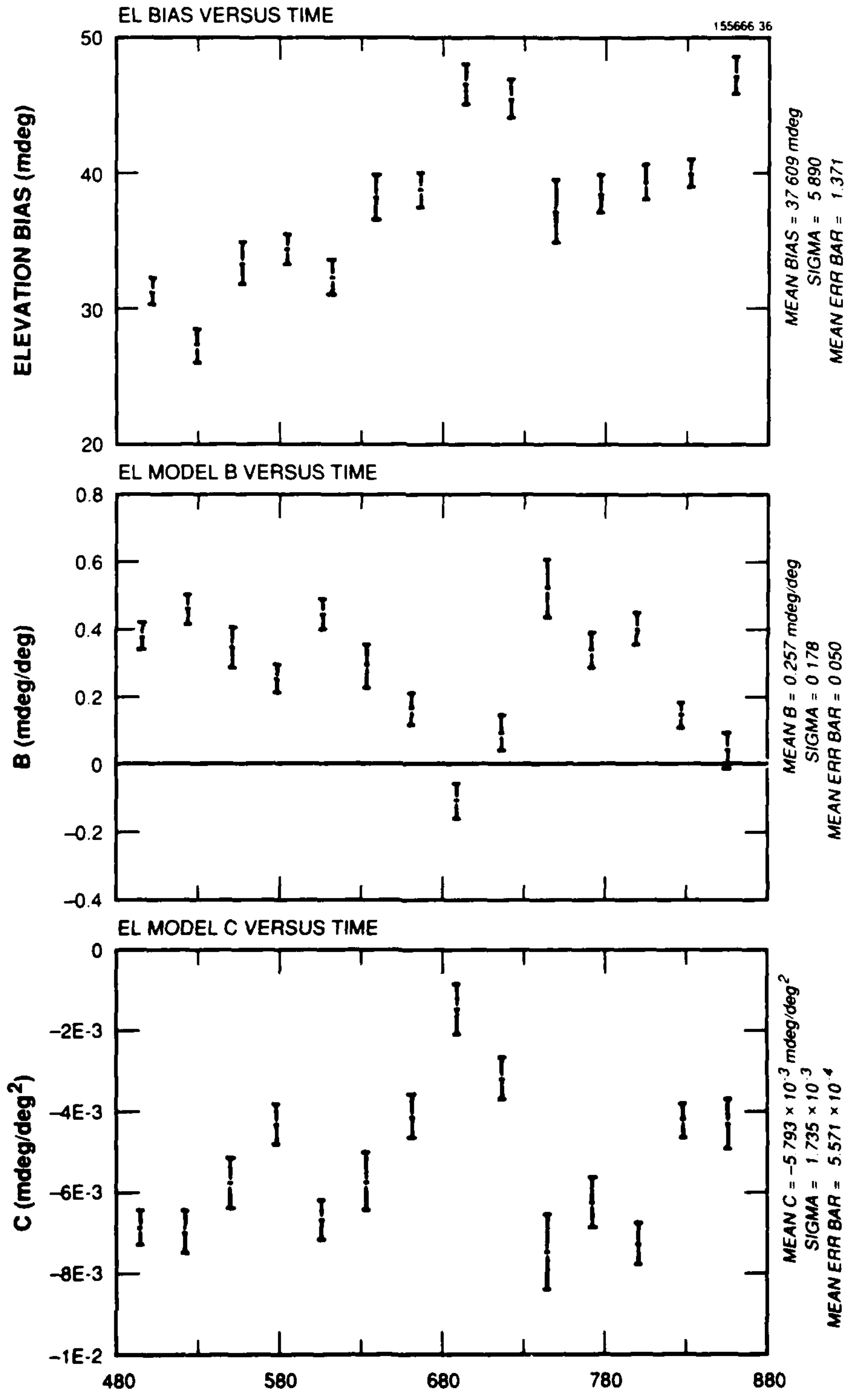
APPENDIX H
LAGEOS ELEVATION MODEL PARAMETERS: RISING ELEVATION DATA

LAGEOS: RISING EL DATA ONLY, DECEMBER 1988 — DECEMBER 1989



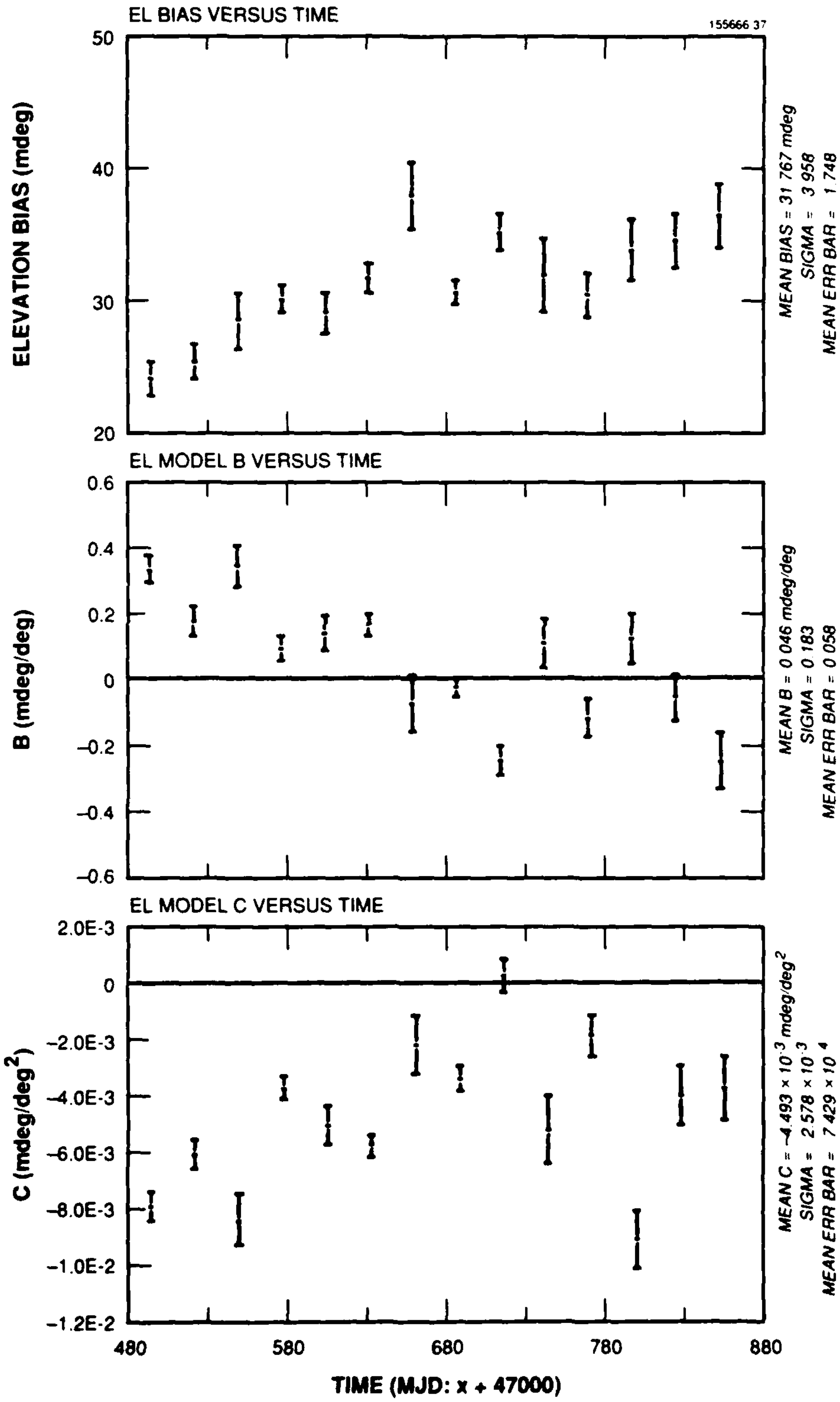
APPENDIX I
LAGEOS ELEVATION MODEL PARAMETERS: FALLING ELEVATION DATA

LAGEOS: FALLING EL DATA ONLY, DECEMBER 1988 — DECEMBER 1989



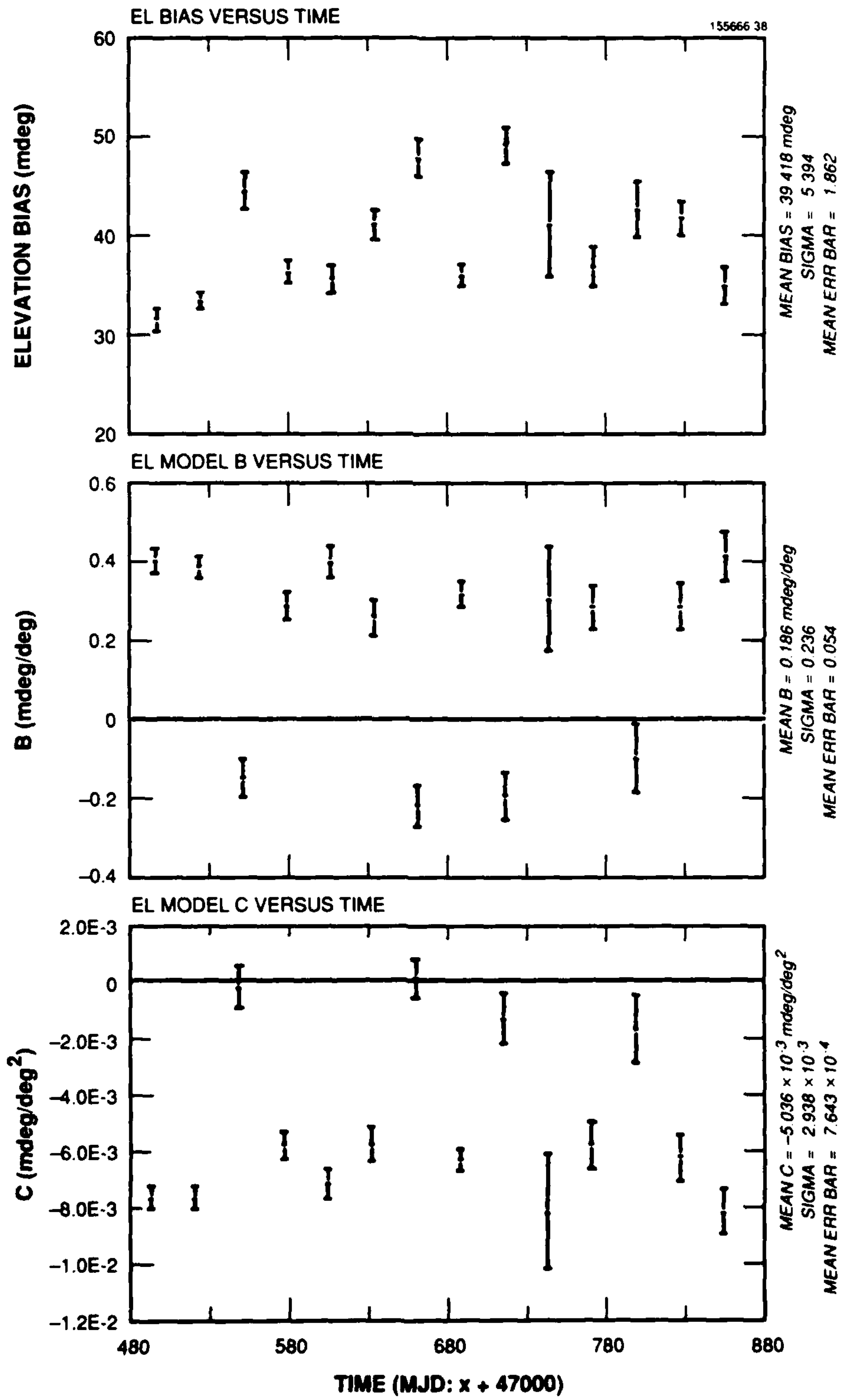
APPENDIX J
EGP ELEVATION MODEL PARAMETERS: RISING ELEVATION DATA

EGP: RISING EL DATA ONLY, DECEMBER 1988 — DECEMBER 1989



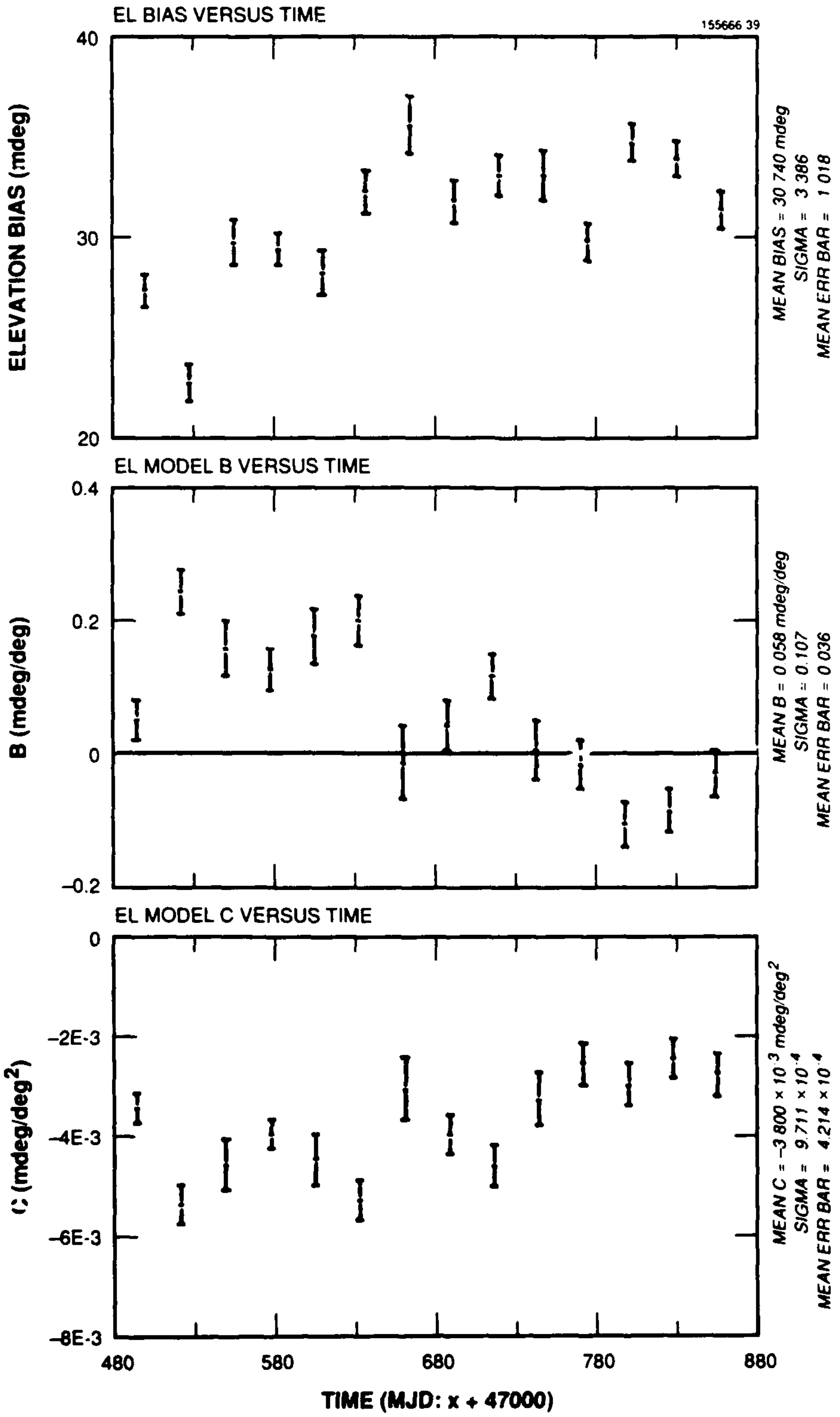
APPENDIX K
EGP ELEVATION MODEL PARAMETERS: FALLING ELEVATION DATA

EGP: FALLING EL DATA ONLY, DECEMBER 1988 — DECEMBER 1989



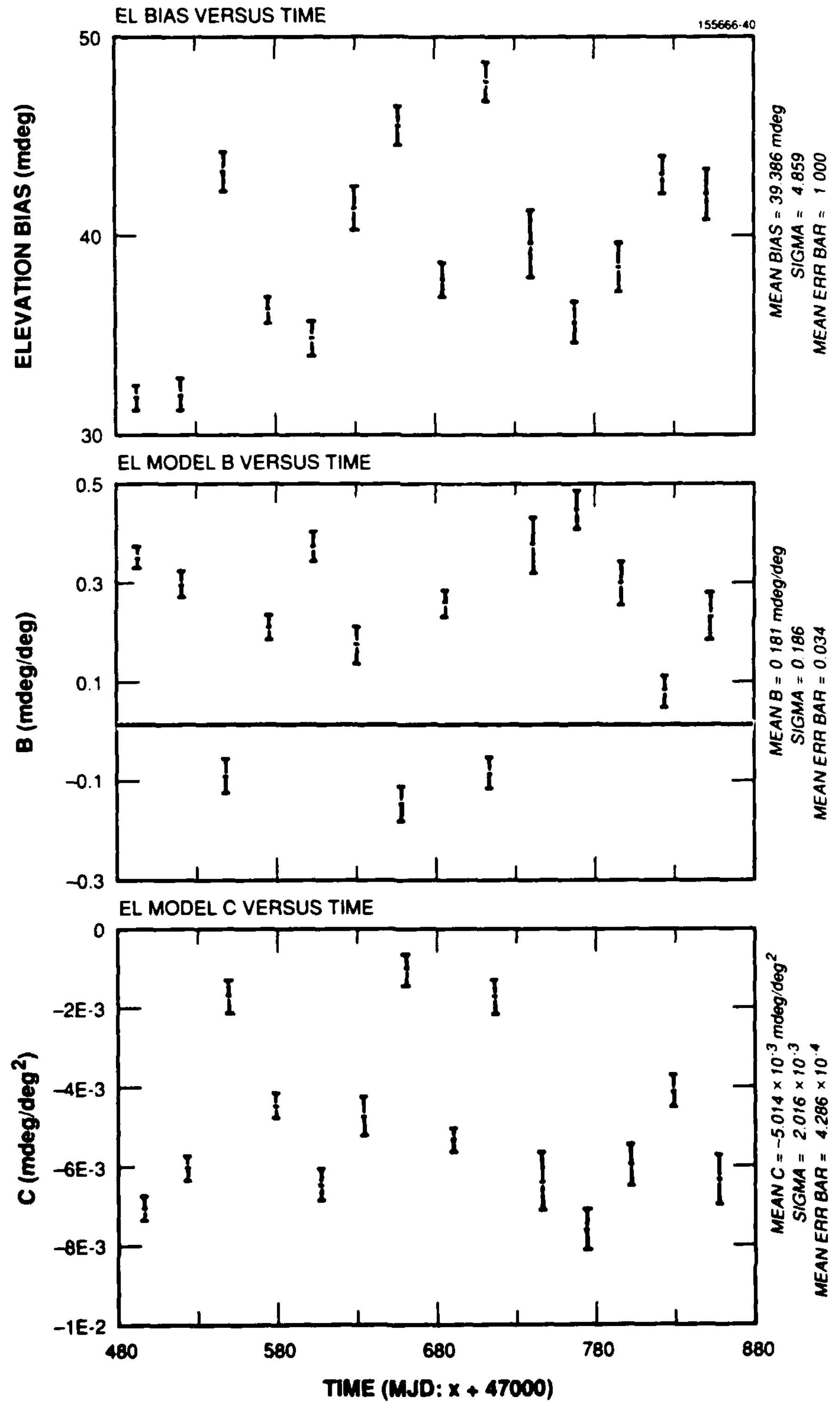
APPENDIX L
JOINT ELEVATION MODEL PARAMETERS: RISING ELEVATION DATA

LAGEOS + EGP: RISING EL DATA ONLY, DECEMBER 1988 — DECEMBER 1989

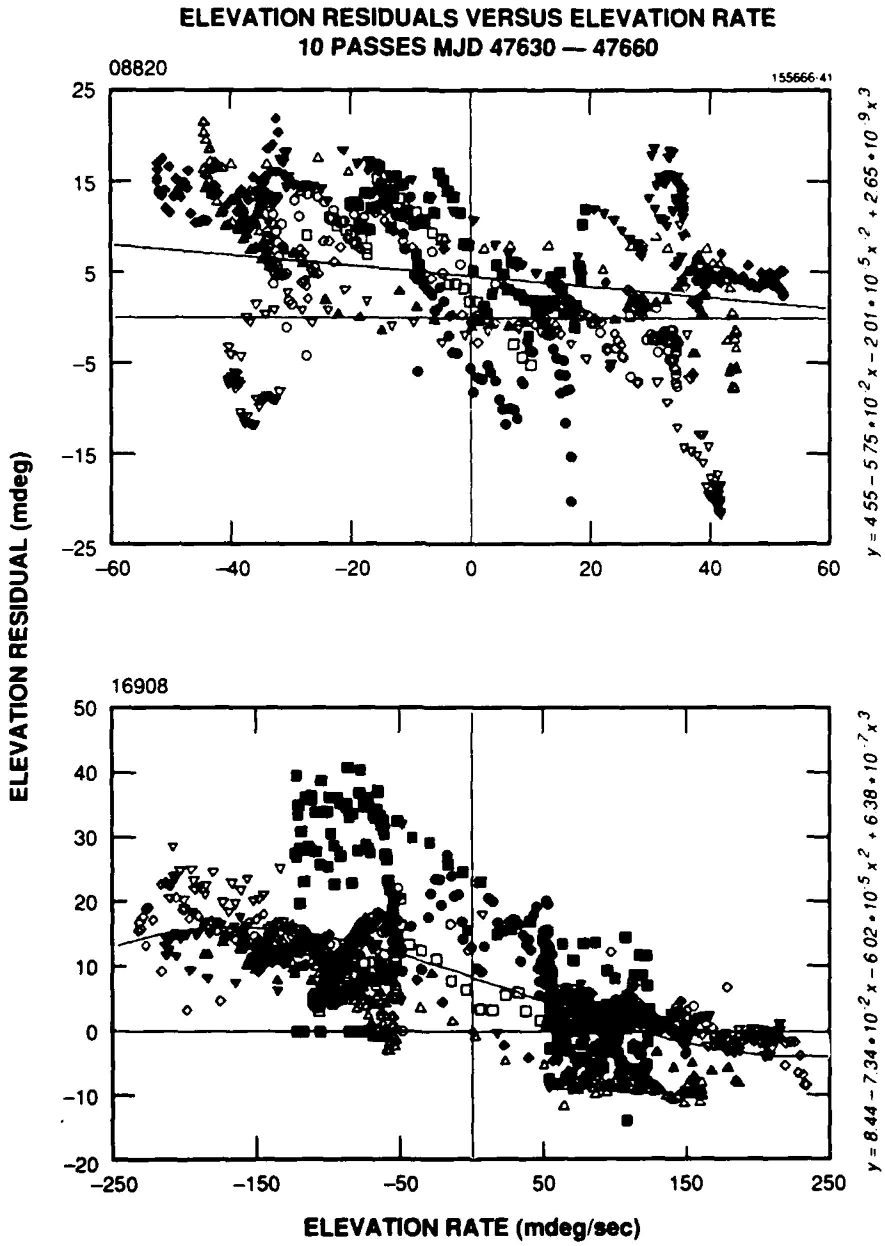


APPENDIX M
JOINT ELEVATION MODEL PARAMETERS: FALLING ELEVATION DATA

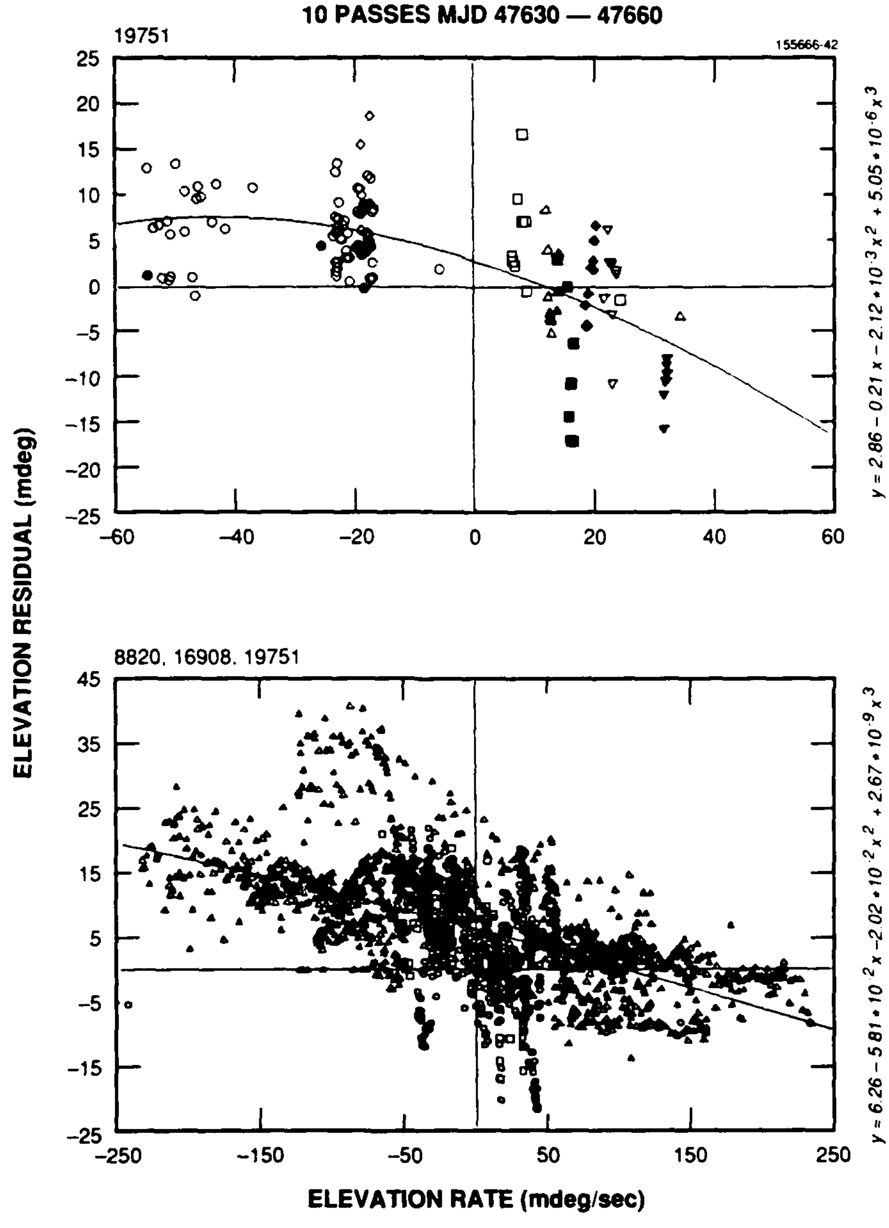
LAGEOS + EGP: FALLING EL DATA ONLY, DECEMBER 1988 — DECEMBER 1989



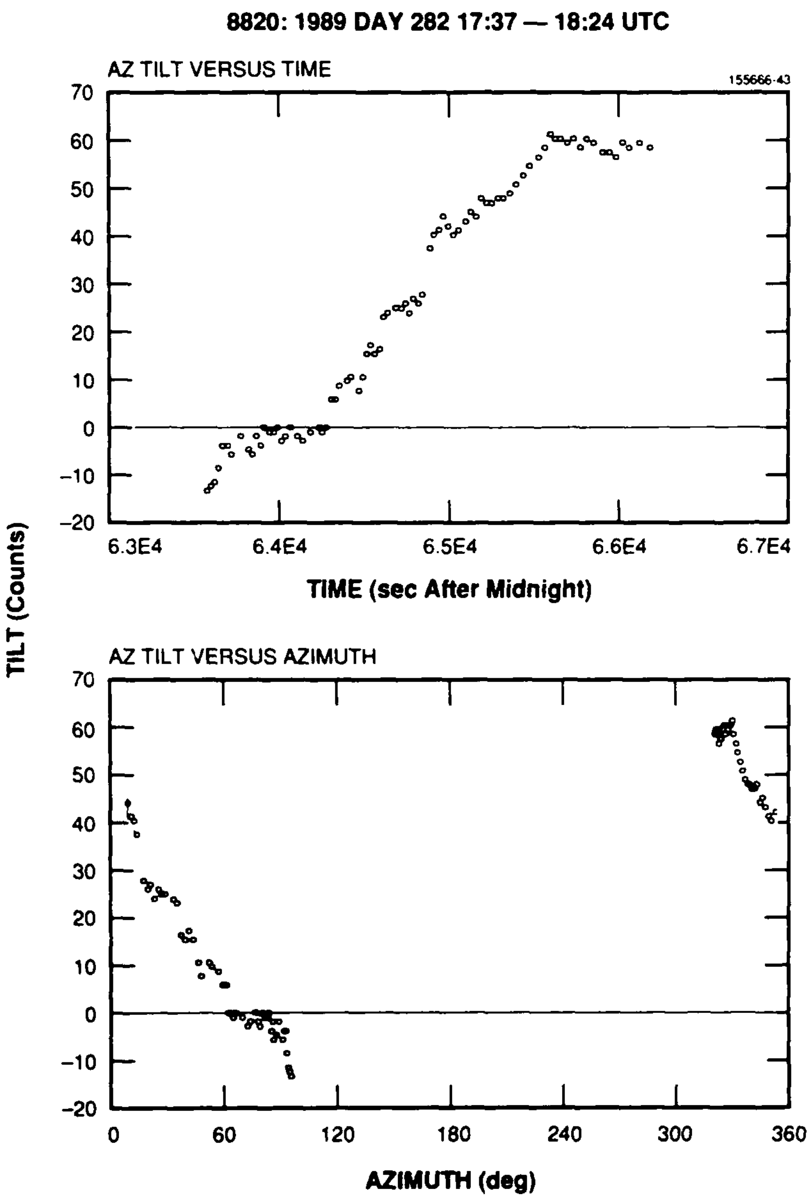
APPENDIX N
ELEVATION RESIDUALS VERSUS ELEVATION RATE



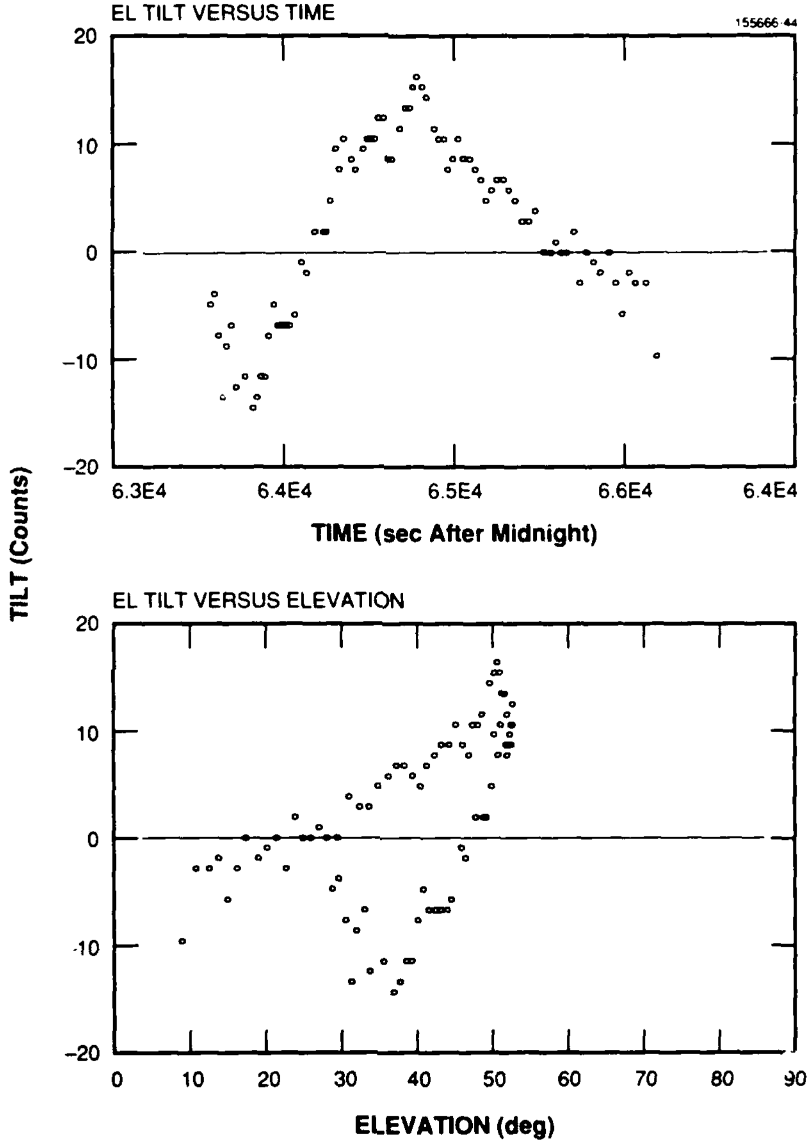
ELEVATION RESIDUALS VERSUS ELEVATION RATE
10 PASSES MJD 47630 — 47660

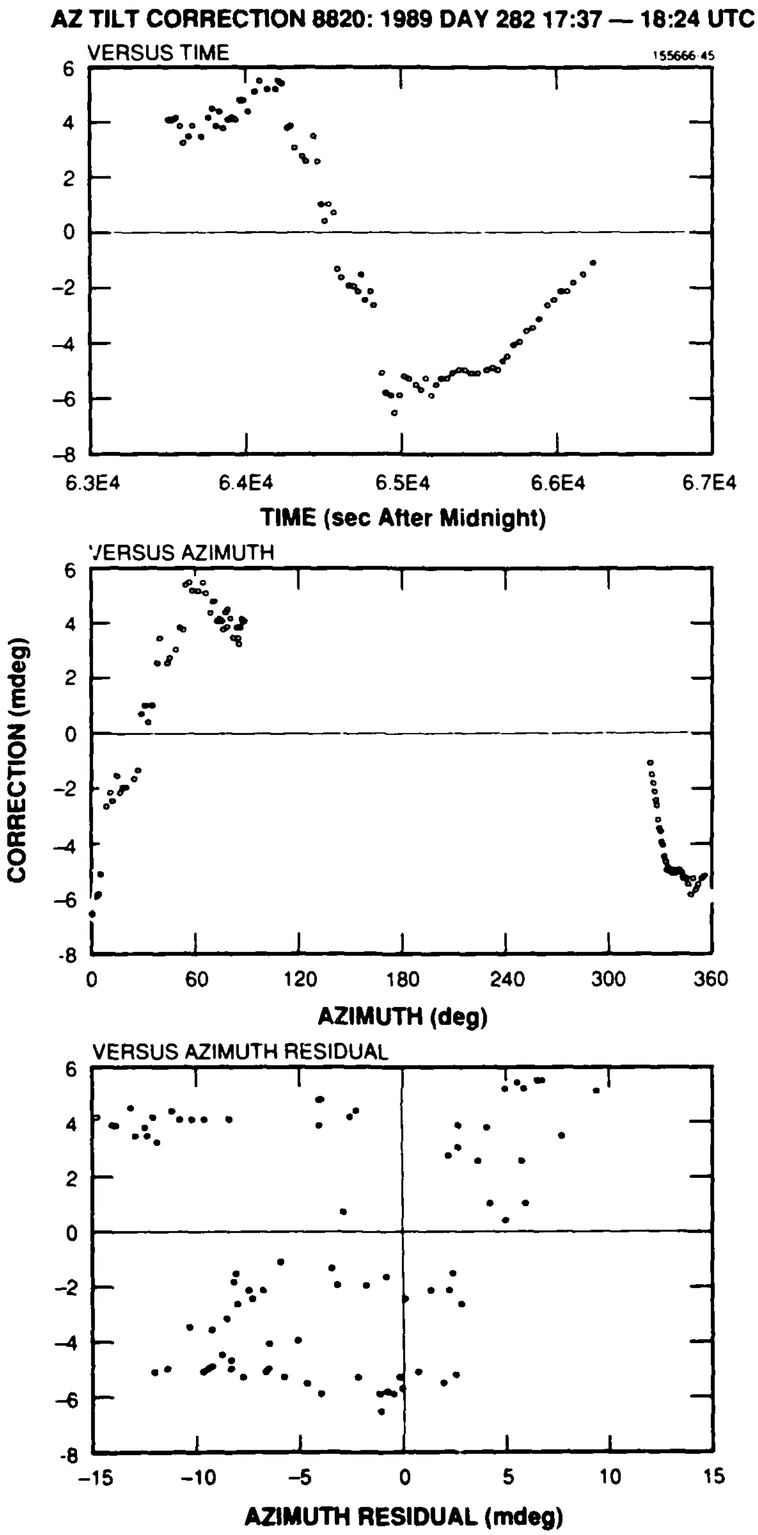


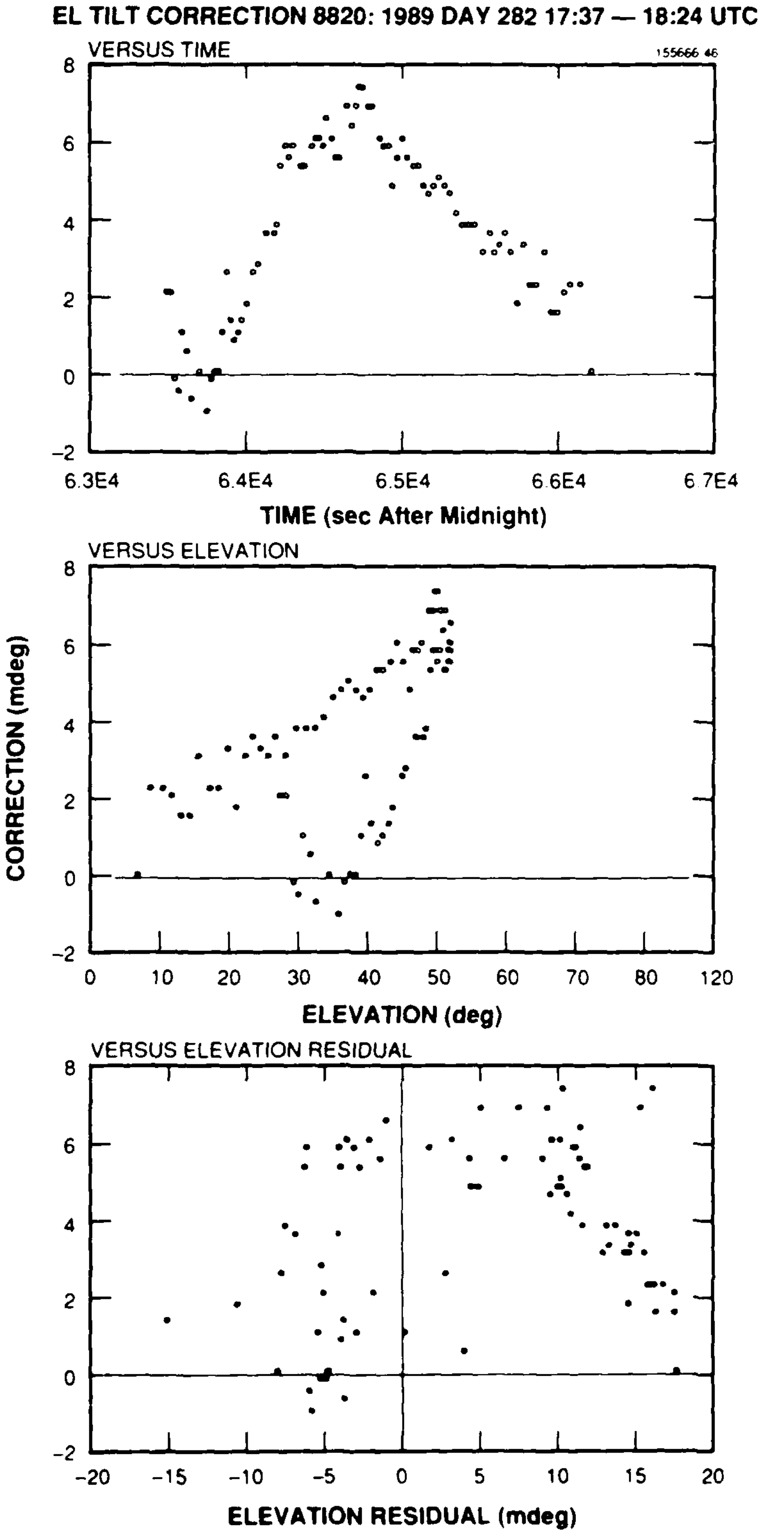
APPENDIX O
TILTMETER DATA



8820: 1989 DAY 282 17:37 — 18:24 UTC




AZ TILT CORRECTION 8820: 1989 DAY 282 17:37 — 18:24 UTC
VERSUS TIME
155666 45
6
4
2
0
-2
-4
-6
-8
6.3E4
6.4E4
6.5E4
6.6E4
6.7E4
TIME (sec After Midnight)
VERSUS AZIMUTH
CORRECTION (mdeg)
0
60
120
180
240
300
360
AZIMUTH (deg)
VERSUS AZIMUTH RESIDUAL
−15
−10
−5
0
5
10
15
AZIMUTH RESIDUAL (mdeg)


EL TILT CORRECTION 8820: 1989 DAY 282 17:37 — 18:24 UTC
VERSUS TIME
155666 46
TIME (sec After Midnight)
VERSUS ELEVATION
CORRECTION (mdeg)
ELEVATION (deg)
VERSUS ELEVATION RESIDUAL
ELEVATION RESIDUAL (mdeg)

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
14 September 1990

3. REPORT TYPE AND DATES COVERED
Technical Report

4. TITLE AND SUBTITLE
Millstone Angle Calibration 1989

5. FUNDING NUMBERS
C — F19628-90-C-0002
PE — 12310F, 12424F
PR — 77

6. AUTHOR(S)
Ann L. Williams

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lincoln Laboratory, MIT
P.O. Box 73
Lexington, MA 02173-9108

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-896

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Space Command
Peterson AFB
Colorado Springs, CO 80914-5001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ESD-TR-90-088

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Calibration of the Millstone Hill radar is accomplished by the use of several calibration models. This report focuses on the two models used to calibrate azimuth and elevation. Data from both low-altitude and deep space satellites for the year 1989 were used for this study. Of particular interest is the variation of the calibration model parameters over time. This study considers the methods by which these parameters should optimally be determined, and the frequency with which they should by updated. In addition, attempts to model an unexplained jump seen in elevation residuals are discussed. Finally, the tiltmeter calibration models are examined.

14. SUBJECT TERMS
calibration
radar calibration
angle calibration
precision orbit determination
Lageos
EGP
Etalon

15. NUMBER OF PAGES
104

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR